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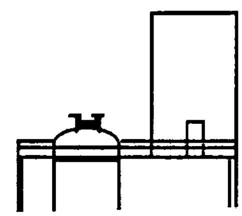
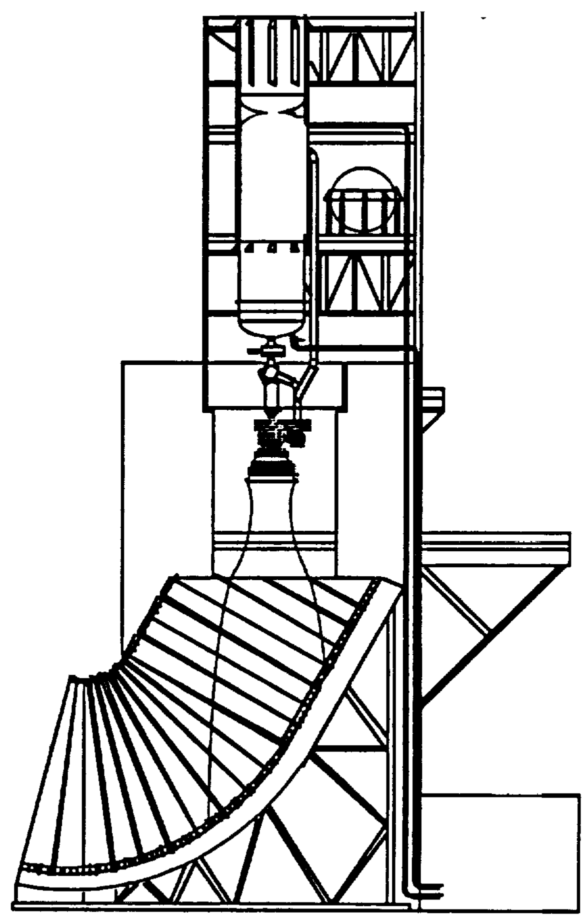
Volume II
Technical Report

Propellant Tank Pressurization System Technology Program





MARTIN MARIETTA
MANNED SPACE SYSTEMS

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FOREWORD

This document provides the Technical Report, Volume II, for the Propellant Tank Pressurization System Technology Program performed under NASA Contract NAS8-37666. The report was prepared by Manned Space Systems, Martin Marietta Corporation, New Orleans, Louisiana, for the NASA/Marshall Space Flight Center (MSFC).

The study team which participated in this program included Martin Marietta Manned Space Systems, Aerojet Propulsion Division, Atomic Energy of Canada, and Honeywell, Inc.

The MSFC Contracting Officer Technical Representative is Dale Blount. The Martin Marietta study manager is John Cool.

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ACRONYMS AND ABBREVIATIONS

AlLi	Aluminum Lithium
BITE	Built-In Test Equipment
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
DDT&E	Design, Development, Test, and Evaluation
DTI	Direct Tank Injection
F/O	Fuel/Oxydizer
FMEA	Failure Modes and Effects Analysis
ft	Foot (Feet)
GD	General Dynamics
GG	Gas Generator
GHe	Gaseous Helium
GH2	Gaseous Hydrogen
GO2	Gaseous Oxygen
GSE	Ground Support Equipment
H2	Hydrogen
He	Helium
HX	Heat Exchanger
HRB	Hybrid Rocket Booster
IR&D	Independent Research and Development
ISP	Initial Specific Impulse
I/T	Intertank
lb	Pound(s)
LCC	Life Cycle Cost
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
LRB	Liquid Rocket Booster
LRU	Line Replacement Unit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NH3	Ammonia
N2H4	Monopropellant Hydrazine
NSTS	National Space Transportation System

O2	Oxygen
PDR	Preliminary Design Review
psi	Pressure Square Inch
psia	Pressure Square Inch, Absolute
PTF	Propulsion Test Facility
PTPSTP	Propellant Tank Pressurization System Technology Program
RP-1	Rocket Propellant
SC	Supercritical
sec	Second
SL	Sea Level
SOFI	Spray-on Foam Insulation
SOW	Statement of Work
STS	Space Transportation System
TPS	Thermal Protection System
TSE	TestSupport Equipment
TTB	Technology Test Bed
vac	Vacuum
WBS	Work Breakdown Structure

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1.0 INTRODUCTION

The Propellant Tank Pressurization System Technology Program (PTPSTP) is an element of the Booster Technology Program sponsored by the Civil Space Technology Initiative within the office of Astronautics Exploration and Technology. The PTPSTP goal is to demonstrate the acquisition of technology which demonstrates the viability of large propellant tank pressurization systems to provide propellants at appropriate pressures and flow rates for high thrust (750k lb) rocket engines.

1.1 BACKGROUND

The PTPSTP is an outgrowth of the Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Study (contract NAS-837136) conducted for Marshall Space Flight Center (MSFC) Program Development. The LRB study defined optimum pump-fed and pressure-fed booster configurations and identified technology requirements to support booster development. A key technology need identified for the pressure-fed LRB is a large ullage volume, low mass, high flow-rate pressurization system. The LRB study contractors, Martin Marietta and General Dynamics, selected LO2/RP-1 as the preferred propellants for the pressure-fed booster. The Martin Marietta concept pressure-fed engines operate at a combustion chamber pressure of 660 psia. The propellant tank pressure requirement is 1000 psia. The study recommended a pressurization system (Figure 1.1-1) which utilizes an LO2/RP-1 gas generator (GG) and heat exchanger (HX) as the primary energy source to heat the stored helium pressurant.

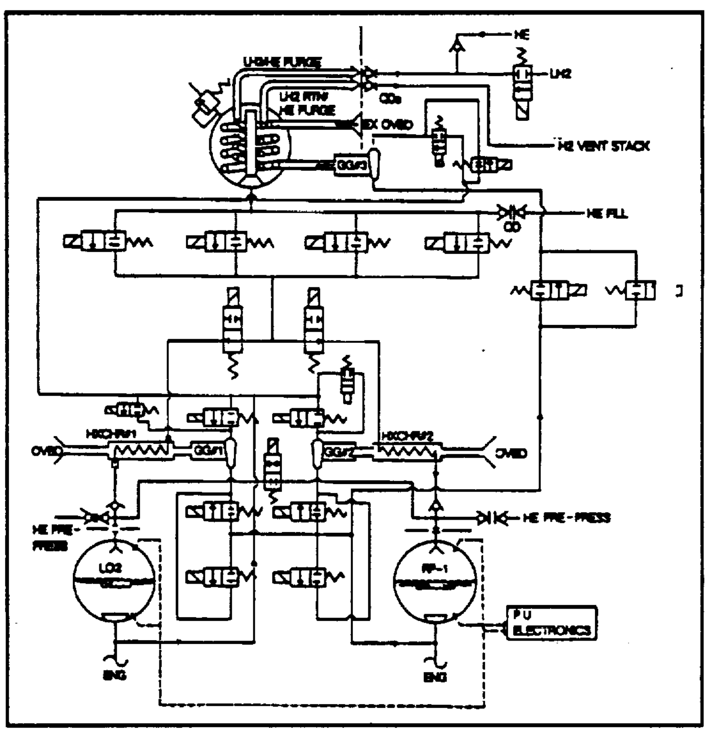

Figure 1.1-1 Martin Marietta LO2/RP-1 Pressurization System

The General Dynamics (GD) booster engines operate at 300 psia combustion chamber pressure and require 600 psia propellant tank pressures. The pressurization system (Figure 1.1-2) recommended by GD uses an O2/H2 catalyst bed as the primary heat source. Both pressurization systems store helium pressurant at cryogenic conditions and high-pressure,

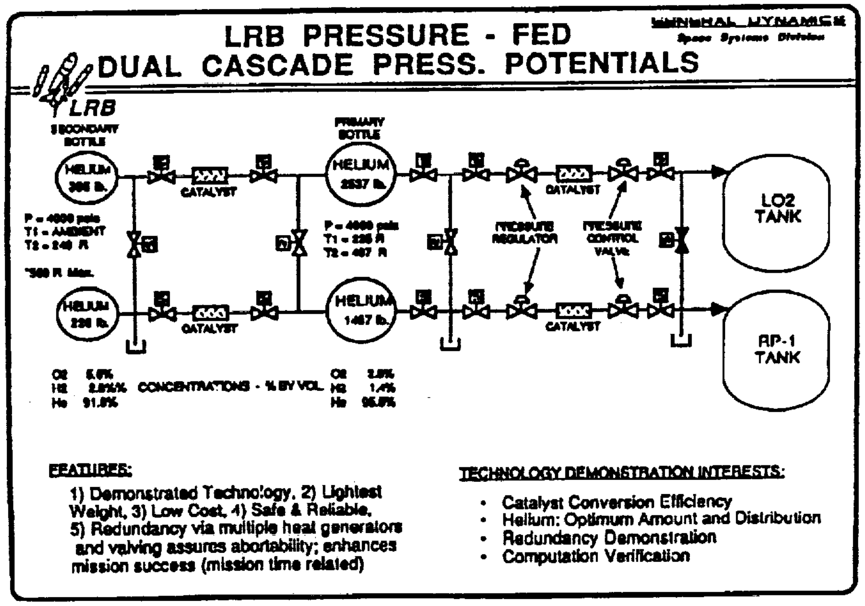

Figure 1.1-2 General Dynamics O2/H2 Pressurization System

expell the stored helium by adding heat to the storage vessel, and heat the expelled helium with a primary heat source before introducing the pressurant into the booster propellant tanks. Figure 1.1-3 is a simplified schematic of the system and illustrates key parameters of each system.

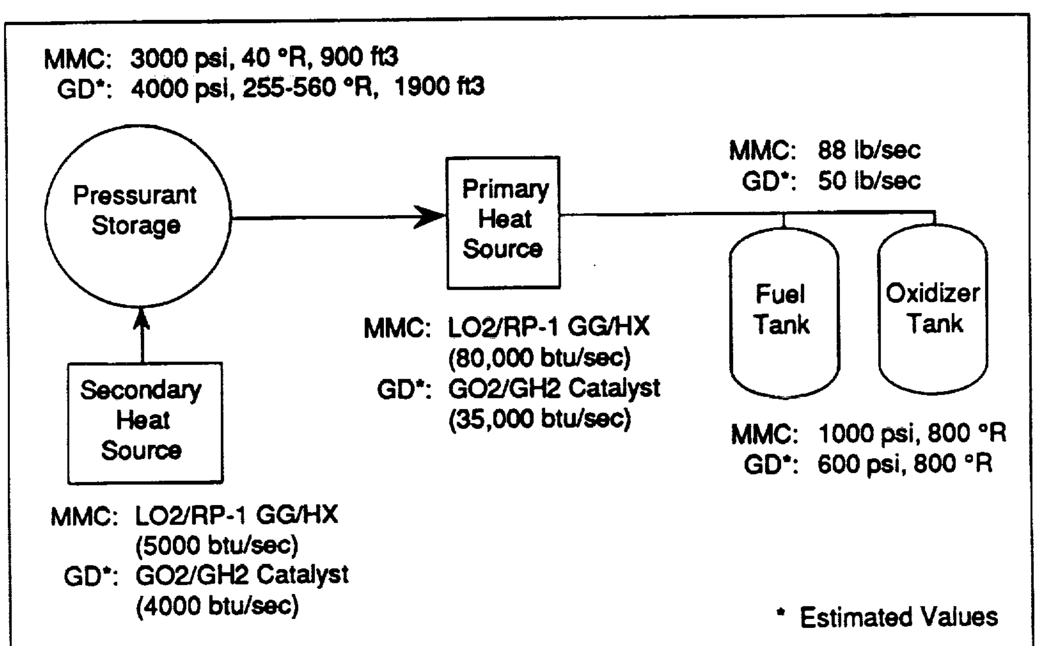

Figure 1.1-3 Simplified Schematic with Temperatures, Pressures, and Flow Rates

The propellant tank pressurization requirements of 1000 psia and 600 psia for the two selected systems in the LRB study impact the total mass of pressurant stored prior to ignition of the engines. Pressurization system packaging in the booster, i.e., volume and location, dictate the number of pressurant storage vessels and their sizes. Storage at colder temperature and/or higher pressures reduces the required volume of the storage vessels. These are some of the considerations that resulted in different systems being chosen by the two LRB study contractors.

The pressurization system data developed in the LRB study is considered a starting point for the PTPSTP systems analyses tasks. Both pressurization system concepts recommended in the LRB study were included as candidates in the PTPSTP system trades. The depth of pressurization system analyses in the PTPSTP significantly exceeded that of the LRB studies and resulted in the recommendation of an alternate system.

1.2 PTPSTP OBJECTIVES AND TASK PLANS

Pressure-fed liquid rocket boosters or hybrid rocket boosters (HRB) offer an attractive alternative to pump-fed LRBs or solid rocket boosters (SRB) for large launch systems such as the Space Shuttle. Pressure-fed propulsion systems can be less complicated and more reliable than pump-fed systems. They have no complex turbomachinery and fewer critical failure modes. They are also more robust than pump-fed systems and approach SRBs with respect to recoverability. Pressure-fed propulsion systems have the potential for lower cost if key technologies can be developed. Because pressure-fed booster technology is less mature than pump-fed or solid booster technology, effort is required to bring the technology to a level where pressure-fed options can be realistically considered for future booster vehicles.

The goal of the Propellant Tank Pressurization System Technology Program is to bring large scale pressurization system technology to a level of maturity demonstrating operational capability and control. The PTPSTP complements the Pressure-Fed Thrust Chamber Assembly Technology Program. These programs will demonstrate the acquisition of key technologies for a pressure-fed LRB and partial technology for a pressure-fed hybrid booster.

The objectives of the PTPSTP were to explore, develop, and demonstrate tank pressurization technology for pressure-fed liquid and hybrid booster systems. In order to accomplish this, the program was structured to research potential pressurization system candidates, select the most suitable pressurization system concepts, identify technology needs, and acquire the needed technology. The completed program would validate the integrated pressurization system technology in simulated booster tests.

The PTPSTP was structured into four serial tasks to meet the above program objectives. Figure 1.2-1 presents the PTPSTP task flow. Task I included all of the studies and analyses leading to the selection of a flight pressurization system concept. Potential pressurization system concepts were identified and screened to establish a list of suitable candidates that would meet the system requirements. These candidates were evaluated further in system trade studies to arrive at system concepts for optimization and final system selection. The final candidates were optimized to best satisfy the system requirements (Appendix A), and system trade studies were performed to select the best flight system concept.

Task II included activities to identify and plan the acquisition of enabling and enhancing technologies needed for the development of the selected flight pressurization system. These technologies were identified, categorized as enabling or enhancing, and prioritized. A detailed technology acquisition plan (Appendix B) was prepared and is consistent with the category and priority of the identified technologies.

Task III initiated the implementation of the technology acquisition plan developed in Task II. Implementation activities included analysis of related technology, component performance and the development of computer models. Tests of critical components to demonstrate technology acquisition were also included. Test results would be used to validate and calibrate the computer models.

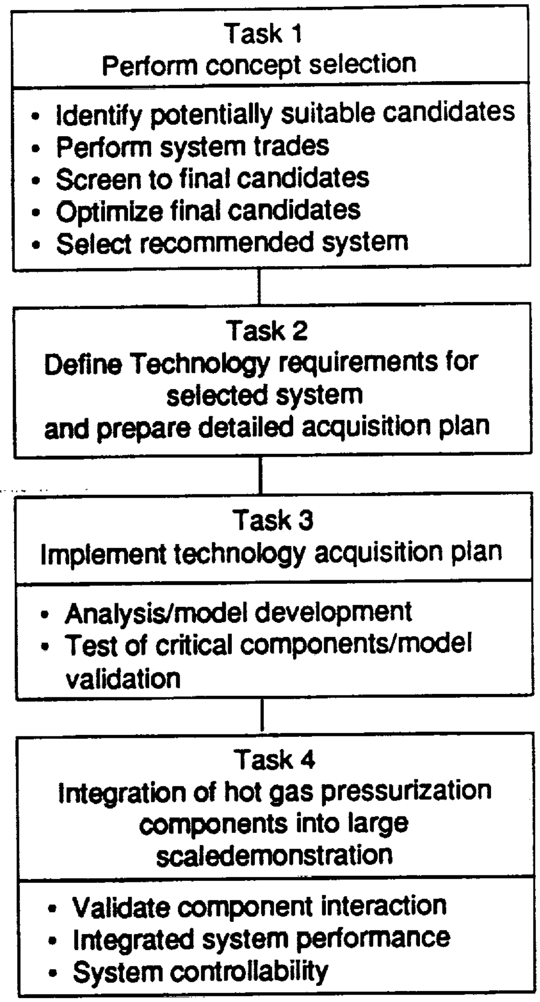

Figure 1.2-1 Approach to Meeting PTPSTP Objectives

Task IV activities included the development or acquisition of system components to produce a large scale pressurization test article and the integration of the test article into the propulsion test facility (PTF) at MSFC. Once installed in the PTF, testing of the total system would validate the pressurization system component interactions. Component interactions within the pressurization system and with the rest of the propulsion technology simulator would be defined. The total integrated system performance would be demonstrated and pressurization system controllability would be evaluated.

The propellant tank pressurization system options that were analyzed, compared, and ultimately optimized into the selected flight pressurization system (Task I) were configured to meet a set of basic vehicle system and design requirements. The basis for these were the requirements set forth in *National Space Transportation System (NSTS) 07700* (Volumes I and X) and derived requirements developed during the Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Systems Study.

The *NSTS 07700* documents contain the basic Level I and Level II requirements for the Space Shuttle and include mission, safety, and reliability requirements. The LRB derived

Table 1.2-1 Pressurization System Flight Article Requirements

- Satisfy STS Level I & II requirements per *NSTS 07700*
- Propellants: LO2/RP-1
- Tank pressure: 600 - 1350 psia
- Propellant flow rate: L02* 1665 - 7990 lbm/sec
  RP-1 1665 - 3330 lbm/sec
- Boost Time: ~120 - 150 sec
- LRB Engine-out capability
- Throttleable over pressure and flow rate rate ranges
- High reliability
- Safety per man-rated standards
- Package in acceptable volume
- Acceptable weight
- Acceptable cost
- Acceptable technical risk

* Includes LRB and hybrid requirements

Table 1.2-2 LRB Study Flight Pressurization System Derived Requirements

Propellant Tanks	Material	LO2 Vol (ft3)	RP-1 Vol (ft3)	Ullage Vol (%)	Max Ullage Temp (°R)	TPS (SOFI)
	Weldalite™ 049 AlLi	12,012	6,326	5	800	1" (LO2 tank only)

Propellants	Density (lbm/ft3)	Mass Flow Rate (lbm/sec)	Volumetric Flow Rate ft3/sec)
LO2	71.1	8068.5	113.5
RP-1	50.5	3022.0	59.8

4 Engines * (throttleable) **	Thrust SL (lb)	ISP (SL)	ISP (Vac)	Mixture Ratio	Burn Duration (sec)	100 % Throttle (sec)	75 % Throttle (sec)	Propellant Flow Rate (lbm/sec)
	750,000	270.5	318.0	2.67	120	30	30-120	11,090.5

* ± 5% band width on propellant tank pressure set point

** Must have capability to throttle 3 engines to 100 % for 30 to 120 seconds to complete mission with a single engine failure

requirements that govern the PTPSTP are items such as propellants (LO2/RP-1), LRB engine-out capability, LRB engine throttleability, etc. Additional requirements for the PTPSTP studies were called out in the PTPSTP statement of work (SOW). These included such items as propellant tank pressures, LO2 and RP-1 maximum flow rates, and LRB boost time. The PTPSTP SOW study requirements for flight system analyses are presented in Table 1.2-1. Pressure-fed LRB study derived requirements and associated data are shown in Table 1.2-2.

1.3 STUDY RESULTS SUMMARY

The PTPSTP contract team consisted of four major participants with responsibilities in a specific area of expertise. Martin Marietta Manned Space Systems was the program lead

Table 1.3-1 Flight Pressurization System Selection Process

Concepts Considered	Preliminary Screen	Detailed Screen	Final Screen
LO2/LH2/He Heater	Not Applicable	Passed	Selected
Catalyst	Passed	Passed	Size, Development Risk
GG/HX	Passed	Passed	Size, LCC, Packaging
Fuel Rich GG/Direct	Passed	Reliability, LCC	
Monopropellant Catalyst/Direct Injection	Passed	Safety, Supportability, LCC	
Autogenous LO2 Quasi-Autogenous RP-1	Passed	Reliability, Weight, Supportability, LCC	
Ambient Helium	Not Fail-safe, Residual Hazards, Vehicle Integration		
Oxidizer Rich GG/Direct Injection	Not Fail-safe, Residual Hazards, LO2 Compatability		
Fuel & Oxygen Rich GG/Direct Injection	Not Fail-safe, Residual Hazards, LO2 & RP-1 Compatability		
Fuel & Oxygen Rich Solid GG/Direct Injection	Not Fail-safe, Residual Hazards, LO2 & RP-1 Compatability, Not Verifiable, No Shutdown		
GG Vaporization/Direct Injection	Not Fail-safe, Residual Hazards, LO2 & RP-1 Compatability, Not Verifiable		
Direct Tank Injection/ Combustion	Not Fail-safe, Residual Hazards, LO2 & RP-1 Compatability, Not Verifiable		

and systems integrator. Aerojet Propulsion Division provided combustion device analyses and preliminary design as well as propulsion system analysis support. Honeywell, Inc. performed control system analyses and conceptual design. Atomic Energy of Canada provided catalyst system analyses and conceptual design in support of system trades. The

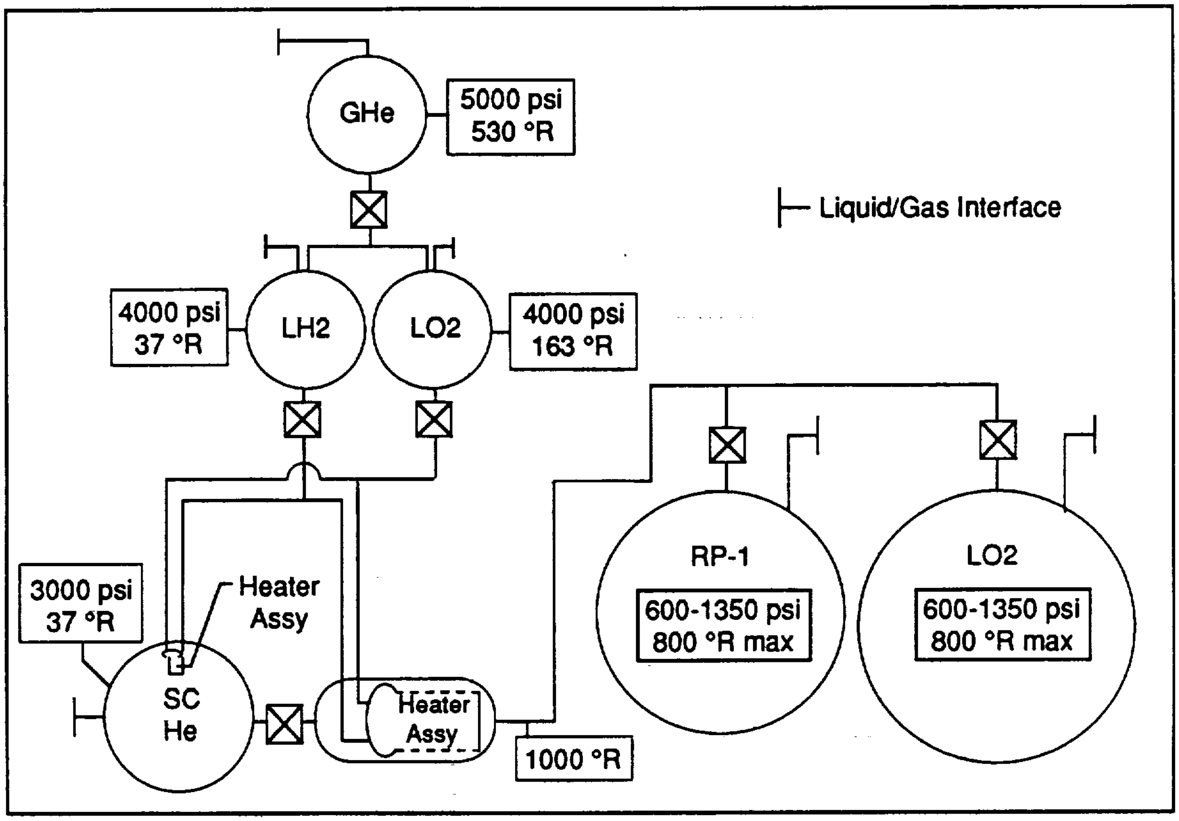

Figure 1.3-1 Selected Pressurization System Simplified Schematic

support contractors' reports are provided as appendices and are referenced in the appropriate sections of this technical report. The following paragraphs summarize the study results by task.

Task I - Task I consists of flight pressurization system concept screening and selection. This task is complete. Table 1.3-1 summarizes the concepts considered and the results of the three-level screening process. Criteria that eliminated various concepts are presented in Section 2.0. The LO2/LH2 helium heater concept was selected. Figure 1.3-1 presents a simplified schematic of the selected pressurization system. The LO2/LH2 helium heater concept was introduced into the trade studies after the preliminary screening. The helium heater is comparable in operation to the catalyst system.

The selected flight pressurization system is a stored pressurant gas system using LO2/LH2 fueled helium heaters for both the primary and secondary heat sources. The helium pressurant is stored as a supercritical fluid at 3000 psia and 37-40°R. This takes advantage of the relatively high density of the helium at these conditions. Within the primary heat source

(LO2/LH2-fueled helium heater), the oxygen and hydrogen burn at near stoichiometric conditions (O/F≈8) and mix with the cold helium pressurant to produce ullage pressurant gas at 900-1000°R.

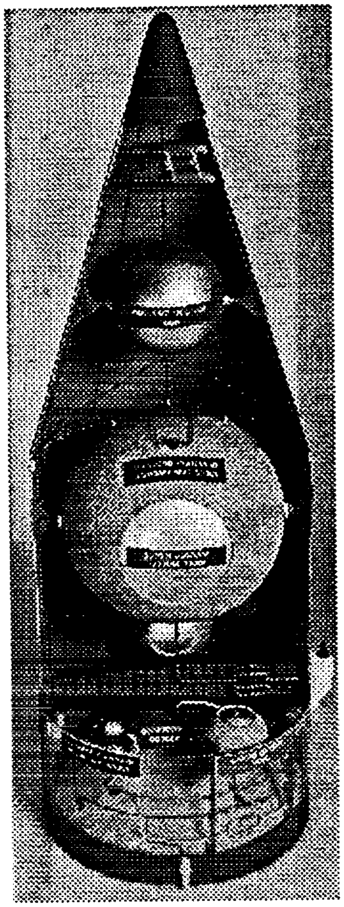

Figure 1.3-2 Selected Pressurization System Model

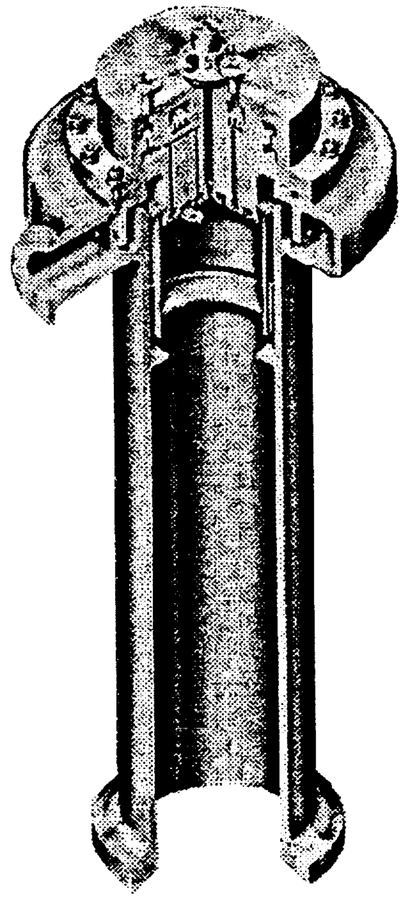

Figure 1.3-3 LO2/LH2 Primary Heater

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The LO2/LH2 secondary heater is also a stoichiometric burner. The burner exhaust flows directly into the helium storage dewar to provide the energy for positive helium expulsion. The maximum percentage of unburned oxygen or hydrogen which could be introduced into the helium flow due to a system failure is well below concentrations required for combustion in either of the propellant tanks. Therefore the system is fail safe for this failure mode. Both heaters are supplied by a pressure-fed LO2/LH2 system using ambient helium at 4000 psia to pressurize the LO2 and LH2 tanks.

Most of the components of the selected system are small and fit easily into an LRB size vehicle. Almost all system components can be housed in the forward skirt and nose cone section of the vehicle (Figure 1.3-2).

Task II - The key technologies needed for the selected concept were identified, and a Task III technology acquisition plan for the selected concept was prepared and submitted to NASA MSFC. Table 1.3-2 summarizes the technology needs identified for the selected pressurization system option.

Technology	Analysis	Component Testing	Large Subscale Testing
Primary Heater Performance			
Mixing Efficiency of Primary Helium Heater	x		x
Mixed Gas Properties Over Operating Range	x		x
System Stability Over Operating Range	x	x	x
Ignition and Startup Characteristics	x	x	x
Water/Ice Management			
Cryogenic Dewar	x		
Propellant Tanks	x		x
Pressurant Dewar Expulsion	x		x
Secondary Heater Performance			
Ignition and Startup Characteristics	x		

Table 1.3-2 Selected Pressurization System Technology Needs

Tasks III and IV - Modification 3 to contract NAS8-37666 reduced the scope of the PTPSTP by discontinuing Task III and IV efforts and requested documentation of the accomplishments of the program in a final report. The primary effort completed in Task III and IV has been the development of a preliminary conceptual design of the LO2/LH2 primary heater.

Figure 1.3-3 illustrates the LO2/LH2 primary heater conceptual design. The heater operates at near stoichiometric conditions with hydrogen and oxygen as propellants. Cryogenic helium is introduced into the heater, and the combustion energy is transferred to the helium by mixing the helium through the device. The discharge temperature of the helium is approximately 900°R. The heater configuration and operating characteristics are documented in Appendix D (Aerojet final report), "Propellant Tank Pressurization System Technology Program".

2.0 SYSTEM TRADE STUDY AND SELECTION METHODOLOGY

The flight propellant tank pressurization system candidate trades and optimization analyses were performed using standard Martin Marietta study methodology[1]. The PTPSTP trade study and system optimization process flow is shown in Figure 2.0-1. This process

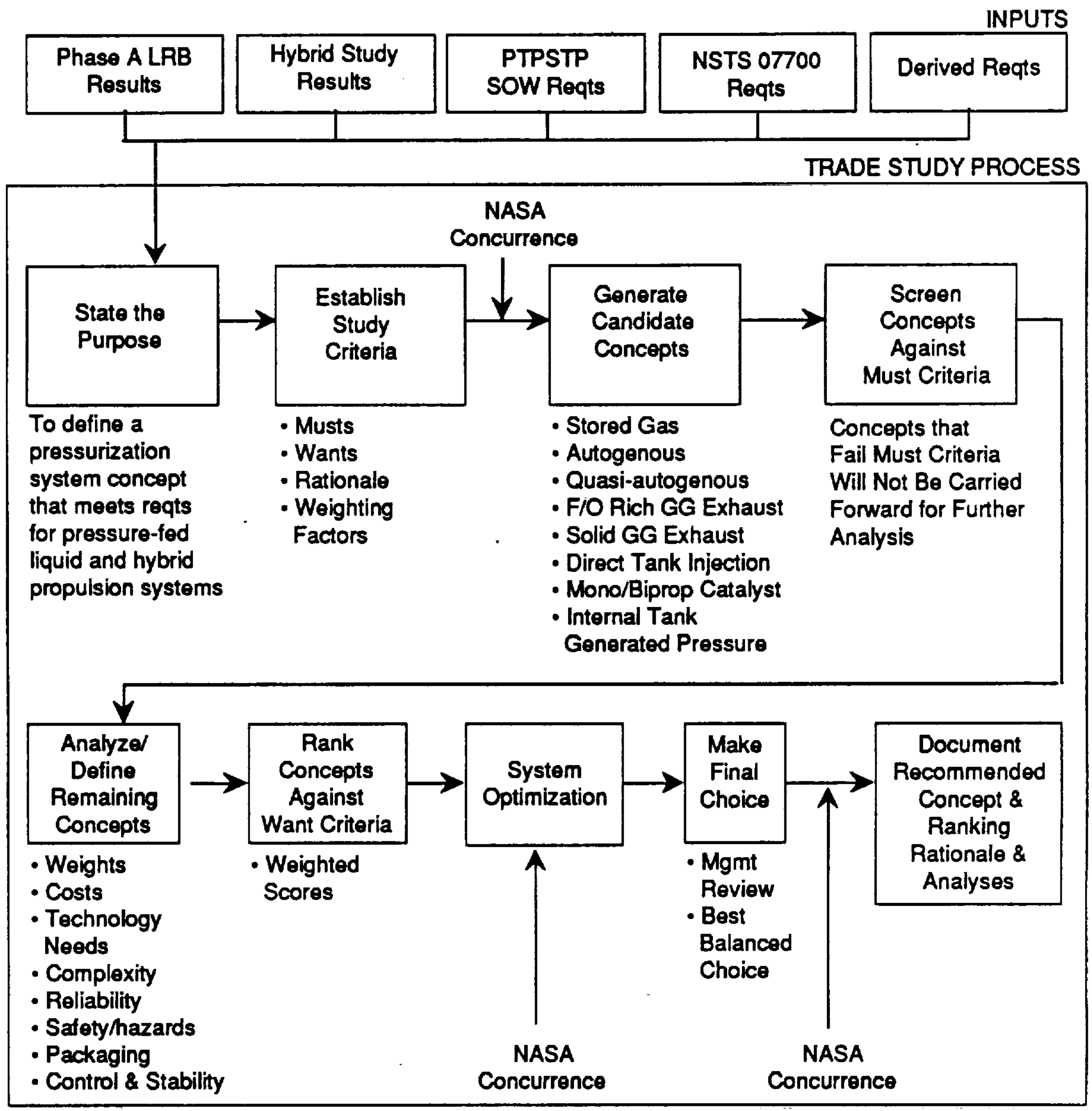


Figure 2.0-1 PTPSTP Trade Study Process

covers the basic steps of establishing the trade study purpose, ground rules, and selection criteria; development of candidate pressurization system concepts; "must" criteria screen; "want" criteria trade; system(s) optimization; and system selection. Table 2.0-1 presents evaluation criteria ground rules. "Must" criteria are used for coarse screening of the

Table 2.0-1 Trade Study Criteria Ground Rules

• Criteria are classified into two categories - "musts" and "wants"
• "Must" criteria are mandatory to fulfill the purpose of the trade
• "Must" criteria serve as a screen to eliminate alternatives
• "Must" criteria should be measurable & quantifiable and represent a go/no go gate
• Alternatives that fail "musts" will not be carried forward for further review
• Criteria that are desirable but not mandatory are considered "wants"
• "Want" criteria provide a selection profile for remaining alternatives and help distinguish between abilities of alternatives
• "Want" criteria are the only ones weighted and used for scoring
• Alternatives are scored against each "want" criterion using a numbering system from 0-10, with the alternative that best satisfies the criteria receiving a 10, others being scored relative to the alternative that scored a 10
• Total weighted scores are used to represent a clear comparison of the performance of the alternatives

Table 2.1-1 "Must" Criteria

Must Criteria	Rationale for Selection
• System shall not be less than fail-safe (except for primary structure, TPS, and pressure vessels) during all mission phases	• *NSTS 07700* Requirement
• Structural/functional integrity shall be verifiable by test	• Implied by *NSTS 07700* Requirement
• System shall be capable of pressurizing LO2 and RP-1 propellants	• PTPSTP SOW Requirement
• System shall be capable of delivering pressurant between 600 and 1350 psia	• PTPSTP SOW Requirement
• System shall have capability for engine shut-down upon command	• LRB Phase A Requirement
• System shall be capable of integration into large pressure-fed liquid and hybrid propulsion systems	• PTPSTP SOW Requirement
• System shall be designed to have no residual hazards (except primary structure, TPS, & pressure vessels)	• Implied by *NSTS 07700* Reqts to Establish Greater System Safety

candidate systems while "want" criteria are used for more detailed evaluation of candidates that have passed the coarse screen.

2.1 COARSE SCREENING OF CANDIDATES

All pressurization system candidates were initially screened for acceptability by comparing them to a set of criteria that a pressurization system must meet. The seven "must" criteria selected for use in the PTPSTP studies are presented in Table 2.1-1. The rationale source that supports each criterion is also shown. Only those candidates that passed this "must" criteria coarse screen were carried on for further trade study evaluation.

2.2 FINE SCREENING OF CANDIDATES

Candidate pressurization systems which passed the coarse screen were analyzed to develop data for scoring against the "want" criteria (Table 2.2-1). The relative importance of each criterion is indicated by the weighting factor assigned. Rationale for each criterion/

Table 2.2-1 "Want" Criteria

"Want" Criteria	Weighting Factor (%)	Rationale for Selection/Weighting Factor
• Safety	20	Safety and reliability identified in SOW as criteria for selecting both future launch vehicles as well as pressurization system - rated most important criteria
• Reliability	20	
• System Packaging	10	Packaging, weight, and supportability identified as criteria for ranking capability to integrate pressurization system into a launch vehicle - not as important as safety and reliability, supportability less important than others
• Weight	5	
• Supportability	5	
• System Performance	10	Complexity identified as criterion in SOW; performance along with complexity provides criteria for ranking system ability to perform its function - together rated less important than safety or reliability
• Operational Complexity	5	
• Technology Needs	5	Technology needs identified in SOW as ranking criterion for developing a viable flight system - rated least important
• Development Risk	5	Development risk and cost identified in SOW as criteria for ranking cost and risk of developing flight hardware - together rated as equal with safety or reliability
• Development Cost	15	
Total	100	Total criteria weight percentages

weighting factor is also presented. Table 2.2-2 defines each "want" criterion and provides the basis of scoring candidates against each. After candidate systems were evaluated and scored against the "want" criteria, the weighted scores were calculated and a total weighted

Table 2.2-2 "Want" Criteria Dictionary

Criteria	Definition	Scoring Basis
Safety	Relative safety of system	Hazard analysis, identification of hazards, and their effects and control methods
Reliability	Relative reliability of system	FMEAs, identification of failure modes, and critical items
System Packaging	Ability of system to be packaged into a launch vehicle	Concept size and ease of integration into the booster, number and type of interfaces, and complexity of load paths will be considered
Weight	Overall weight of pressurization system	Total system weight including inert, gross liftoff, commodities expended, and residuals at engine cutoff
Supportability	Logistics and maintainability of system	Relative comparison of supportability activities, including launch site activities, includes number of system/component checkouts, servicing requirements, and number of LRUs
System Performance	Pressurization system functional integrity	Margin of system to regulate within required operating pressure; to provide control stability by limiting supply line and ullage pressure oscillation frequency and bandwidth, and to exhibit pressure oscillation damping characteristics; and to adjust to varying flow rate demands shall also consider control system complexity and requirements in flight phasing/sequencing operations
Operational Complexity	Overall system complexity	Total number of complex components and prelaunch phasing/sequencing operations
Technology Needs	Required technology advances	Technology needs identified, and cost leverage and schedules to demonstrate technology acquisition
Development Risk	Risk required to achieve required system	Subjective assessment of ability to develop the system and the ability to produce and manufacture the hardware
Development Cost	Cost of achieving required system development	Projected cost to develop and produce flight hardware

score was recorded for each candidate pressurization system. Candidates having the highest weighted scores were then carried forward to the system optimization phase of the study, and a final detailed trade was performed to down-select for the optimum system.

2.3 SYSTEM OPTIMIZATION AND FINAL SELECTION

During the system optimization phase of the study, the highest ranked candidates were analyzed to develop additional data for detailed comparison. The two candidates having the highest weighted scores after optimization were then compared in a risk assessment to arrive at the selected flight pressurization system. The risk assessment covered the areas of technical risk, development risk, and cost/schedule risk.

[1] Engineering Practices, Section SY-1, *Systems Engineering Manual*, Section 4.5, June 1987

3.0 CANDIDATE SYSTEM TRADES

3.1 CANDIDATE PRESSURIZATION SYSTEMS

After a review of all potential pressurization system concepts that could potentially satisfy the requirements of the PTPSTP, twelve pressurization system candidates were chosen for further study. Seven candidates were stored pressurant gas systems. There were two systems that introduced combustion products into the propellant tanks as pressurants; one autogenous/quasi-autogenous system; and two systems where controlled combustion inside the propellant tanks supplied pressurant gas. These candidate systems are listed in Figure 3.1-1. Six stored gas systems loaded the primary helium pressurant as a supercritical fluid ($T \approx 40°R$). One stored gas candidate used ambient helium. The stored gas-steam candidate had two options, and the stored gas-catalyst candidate had three options. As discussed in section 1.1, the optimum pressurization system concept is dependent on pressurization requirements. Pressurization system volume and weight may not be a driver for small propulsion systems, and therefore could be relatively simple compared to large propulsion system requirements. Therefore propellant tank volume and pressure requirements play a significant role in the selection of pressurization system subsystems, i.e., pressurant storage and pressurant heating. A brief description of each candidate system is presented in the following paragraphs.

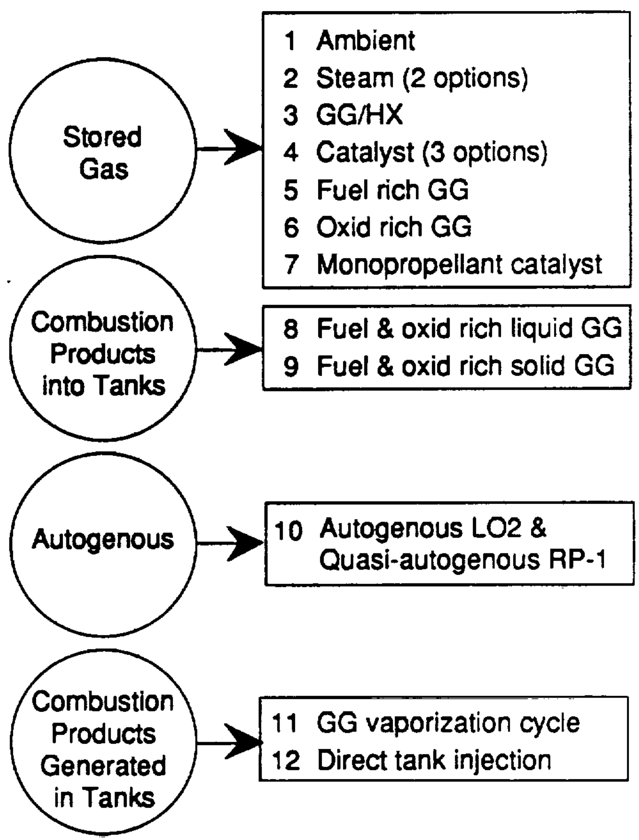


Figure 3.1-1 Pressurization System Candidates

<u>System 1 – Stored Gas-Ambient</u> (Figure 3.1-2) – This system has been used on many small vehicles and has been shown to be the most reliable, safest, and simplest. Scaling from small, low-pressure systems to the PTPSTP requirements forced this system to become very heavy. Isentropic decay of the storage bottle temperature requires very high initial pressure (25,000 psia) in order to satisfy the pressure requirement at the end of the mission. This is why other candidate systems add heat to the pressurant storage vessels. A large tank is required in order to satisfy the pressurant mass requirement. The helium storage vessel weight is over 135,000 lb using the highest specific strength weldable metals available today. Composite materials with impermeable liners necessary to reduce the weight of the system are considered far-term technology for very high-pressure tanks. This system was not highly rated in the trade study.

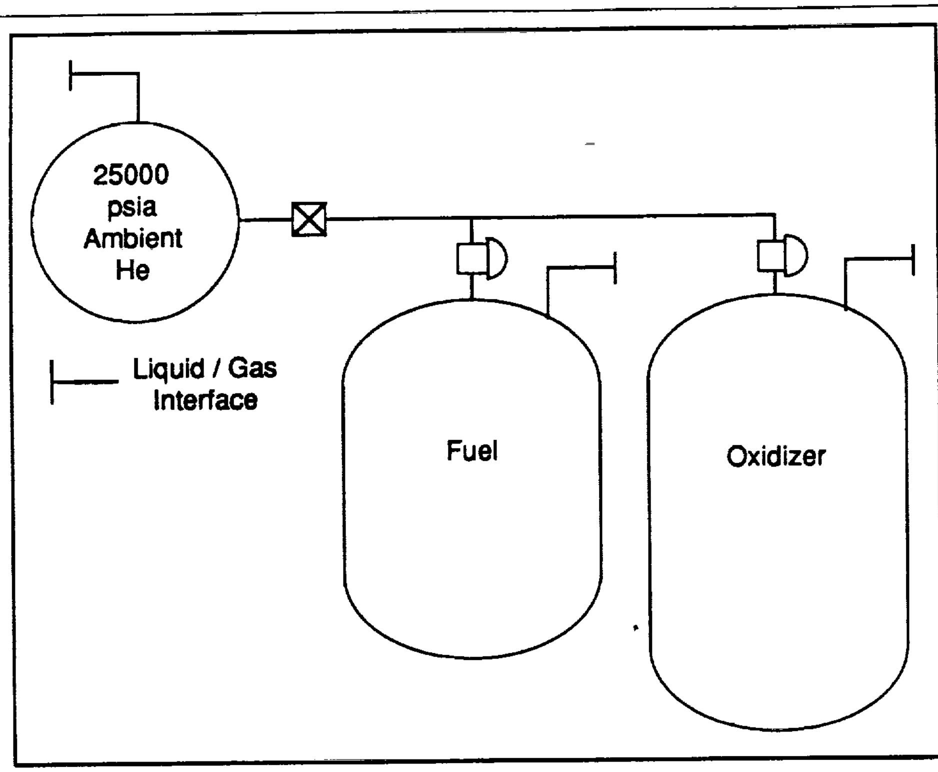


Figure 3.1-2 System 1: Stored Gas – Ambient

System 2 – Stored Gas-GG/Steam (Figure 3.1-3) – This system consists of a cryogenic helium storage tank at moderate pressure (3000 psia). An LO2/RP-1 gas generator (GG) is the primary energy source used to heat the helium and saturated liquid steam is used to

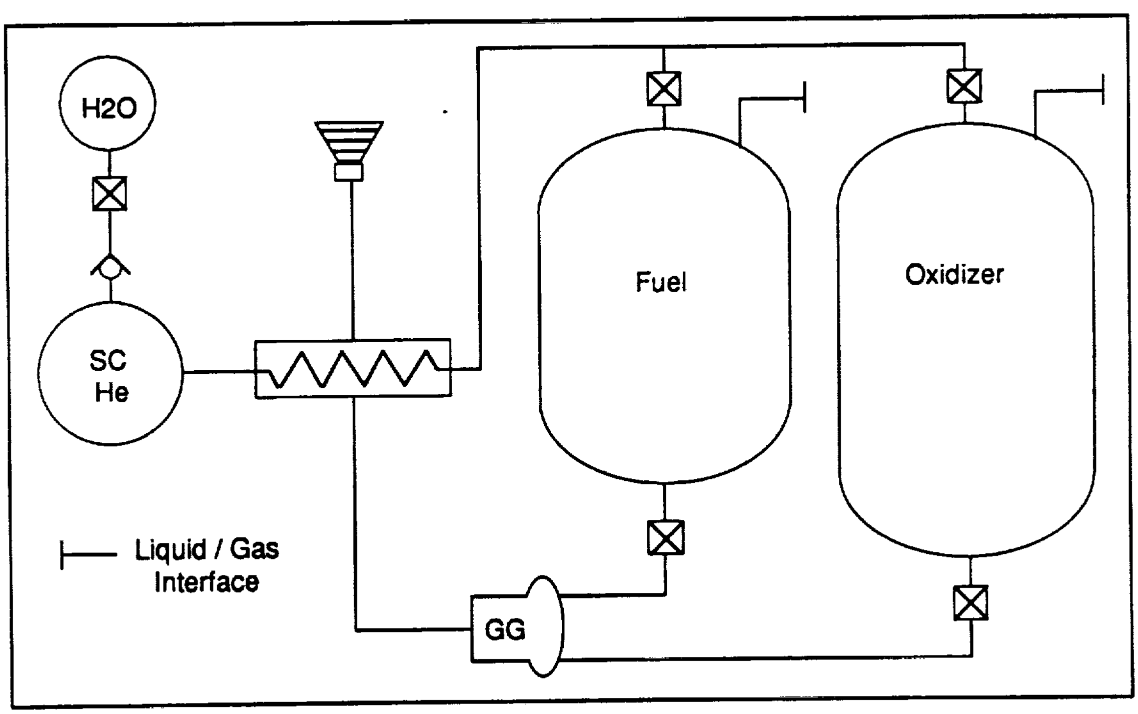


Figure 3.1-3 System 2: Stored Gas – Steam

introduce heat into the helium storage tank. The technologies necessary to bring this system to maturity are a large gas generator/heat exchanger and an understanding of the mechanics of introducing steam into a cryogenic vessel. The system is considered very reliable (i.e. few failure modes and a low likelihood of occurrence) with some reservations about the impact of the ice formed in the helium tank. Ideally, the steam (saturated liquid @ 3100 psia, 1160°R) will flow into the helium tank and freeze, adhering to the tank walls. This will retain the heat from the steam in the tank and minimize the impact of ice in the system. As liquid is withdrawn from the steam tank, the surface will boil at its saturation pressure to sustain tank pressure. An orifice in the line controls the maximum flow rate of the steam and a set of check valves in the line prevent flow of cold helium into the steam line. If the system can be designed so that a small flow of steam is always entering the helium tank, then no opportunity for freezing the line shut will occur. The size and weight of the LO2/RP-1 gas generator/heat exchanger is an issue of scaling because all of the technologies involved are mature. The risk in pursuing the steam/helium technology is moderate.

System 2A – Stored Gas-Steam (Figure 3.1-4) – This system is not technically feasible without a very large steam supply for the mixing chamber. An evaluation of a report from the steam section of National Bureau of Standards (NBS) describing excess enthalpy when mixing steam and helium led to the assumption that the excess enthalpy manifested as a thermal effect. It turned out that the excess enthalpy is actually a density effect in which the steam and helium behave non-ideally when mixed and effectively occupy the same volume that the steam occupies before mixing. Once the mixing phenomena were better understood, the system was not considered a viable alternative.

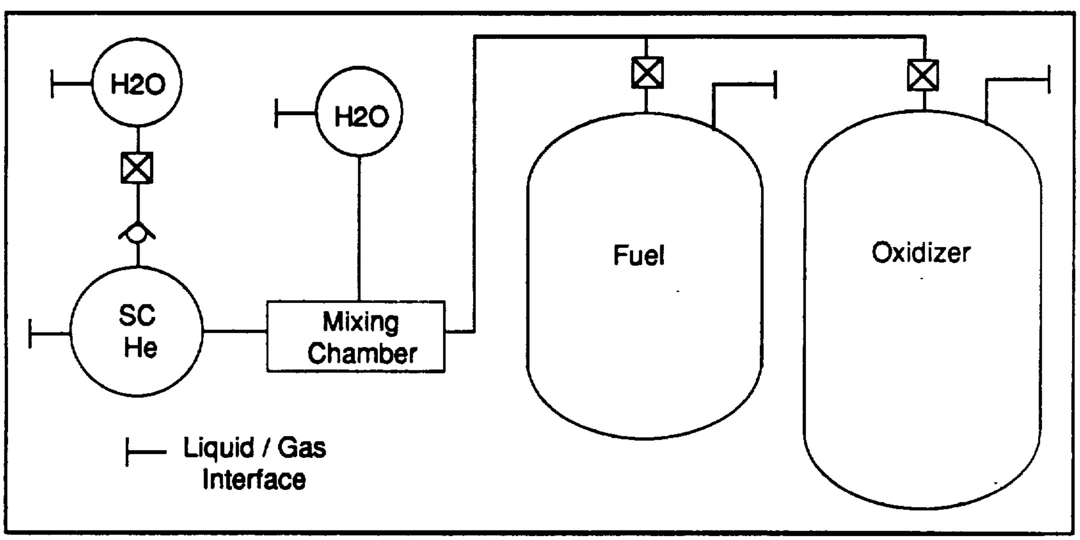


Figure 3.1-4 System 2A: Stored Gas – Steam

System 3 – Stored Gas-GG/HX (Figure 3.1-5) – This system consists of an LO2/RP-1 gas generator and two heat exchangers to provide the primary and secondary heat sources. The technology has been demonstrated on many successful programs in the past. The issues that needed to be resolved to meet the program requirements with this system were packaging within the vehicle, safe exhaust of the gas generator, hot gas, and coking of the heat exchanger which reduces efficiency as run time accumulates. Earlier work performed under contract

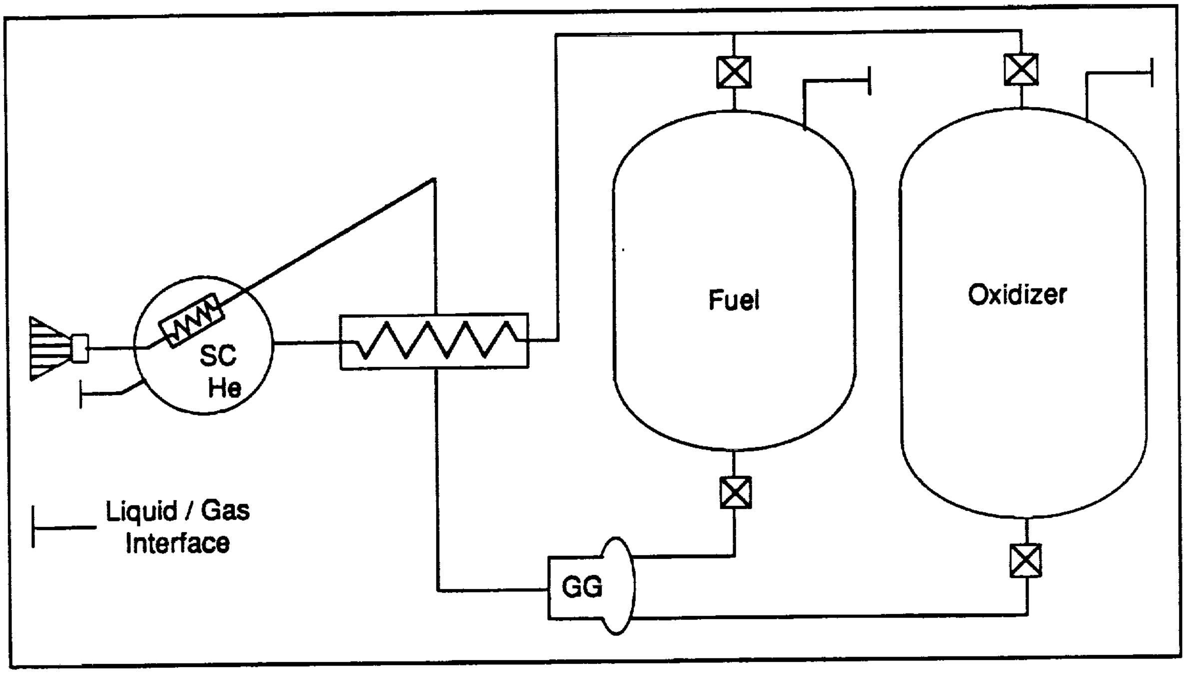


Figure 3.1-5 System 3: Stored Gas – GG/HX

to NASA by Aerojet determined that LO2/RP-1 gas generators produce minimum carbon deposition (not necessarily carbon formation) at a mixture ratio of 0.3. The system was, therefore, sized to operate at this inefficient mixture ratio in order to minimize coking and maintain system components at acceptable temperatures.

The secondary heat source is a heat exchanger located inside the helium tank. The difficulty in packaging the system in the vehicle comes from the need to exhaust hot gas at the rear of the booster, and heat the helium dewar in the nose of the vehicle. This required 12 in. diameter ducts to carry hot gas up and down the vehicle. Efficiency and operability of the system would suffer due to the difficult packaging.

System 4 – Stored Gas-Catalyst (Figure 3.1-6) – This system is driven by catalytic combustion of a mixture of helium, hydrogen and oxygen stored in concentrations below the flammable and detonable limit. Catalyst beds are required to promote combustion. The propellants burn only when flowing through the catalyst. This makes the performance of the catalyst the critical element in the operation of the system. Literature includes many references to catalyst research, but none within the cold, low concentration, nonflammable mixture domain necessary for the function of this particular catalyst application. The effectiveness of the catalyst at low operating temperature is not known. Analytical models were used to predict the performance of the catalyst in the system evaluation.

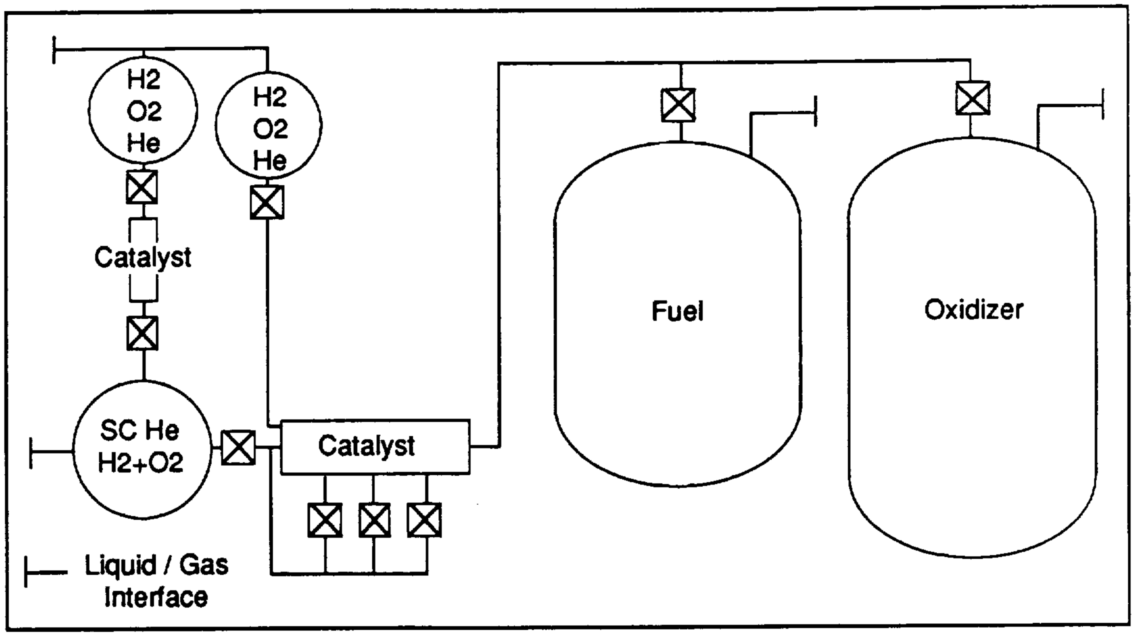


Figure 3.1-6 System 4: Stored Gas – Catalyst

The system uses two ambient temperature, high-pressure O2/H2/He mixture bottles, two catalyst beds, and a single cryogenic O2/H2/He tank. The temperature of the cold helium tank is limited by the fusion or freezing line of oxygen (Figure 3.1-7). The oxygen temperature cannot be allowed to fall below the fusion line because the oxygen will precipitate out of the mixture. This limits the lower temperature of the cold tank to approximately 100°R. A significant decrease in the density of helium occurs between 40°R, 3000 psia and 100°R, 3000 psia. This temperature difference would result in a pressurant storage vessel diameter and mass increase from 13.0 to 15.25 ft and 14,000 lb to 22,000 lb.

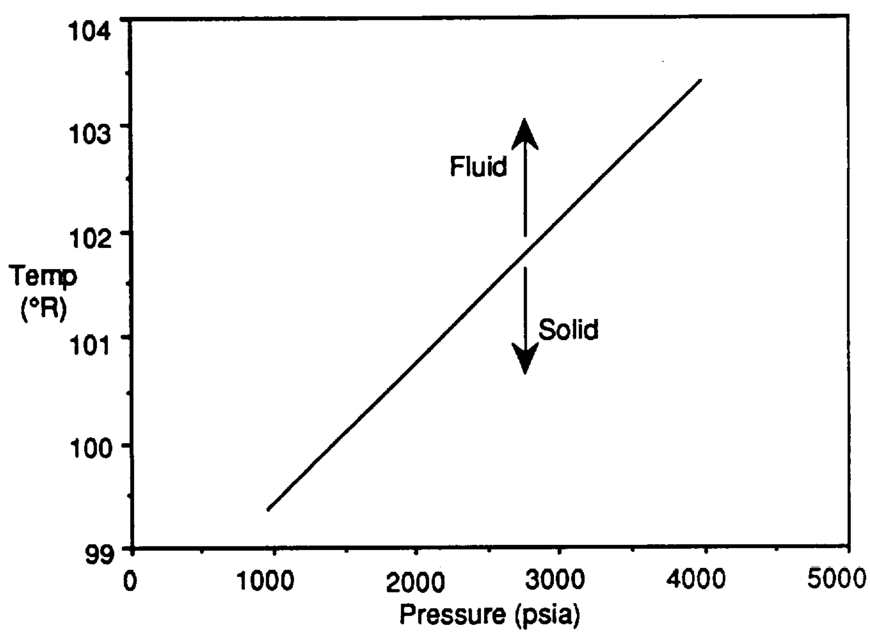


Figure 3.1-7 Oxygen Fusion Line

System 4A – Stored Gas-Catalyst Alternate 1 (Figure 3.1-8) – This system reduces the impacts which resulted in a low score for Candidate 4 in the trade. The oxygen and hydrogen have been removed from the cold helium tank as shown in Figure 3.1-8. The option to retain

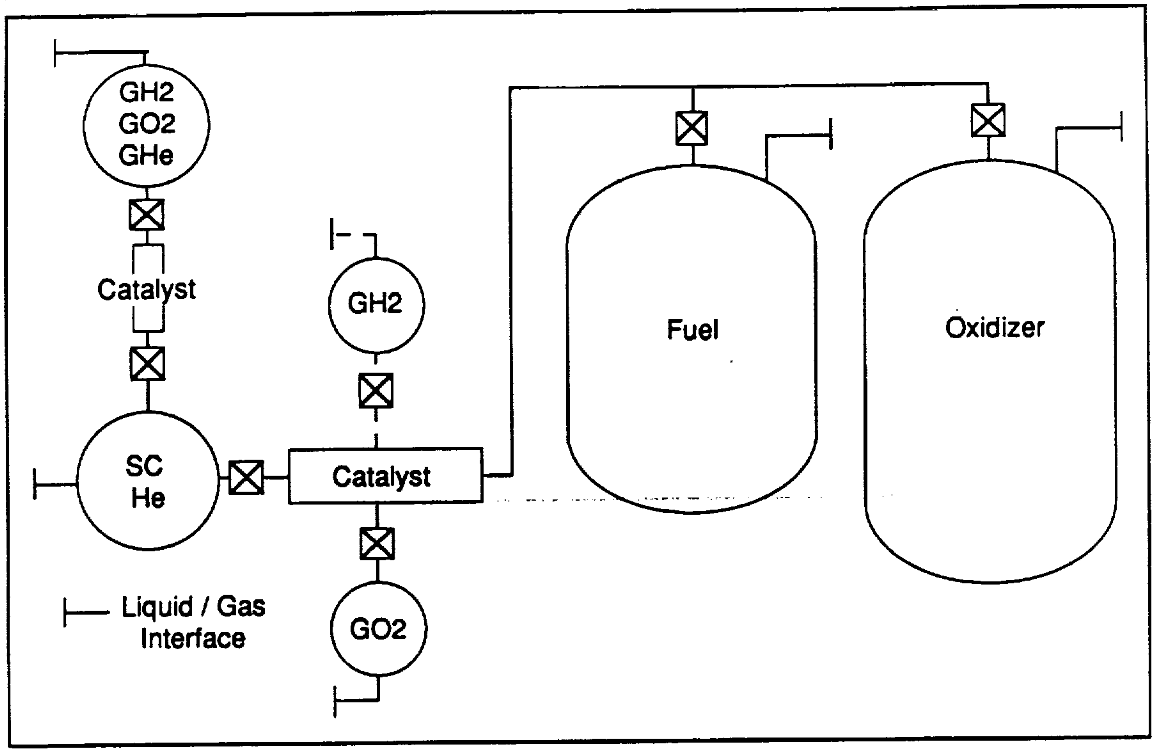


Figure 3.1-8 System 4A: Stored Gas – Catalyst Alternate 1

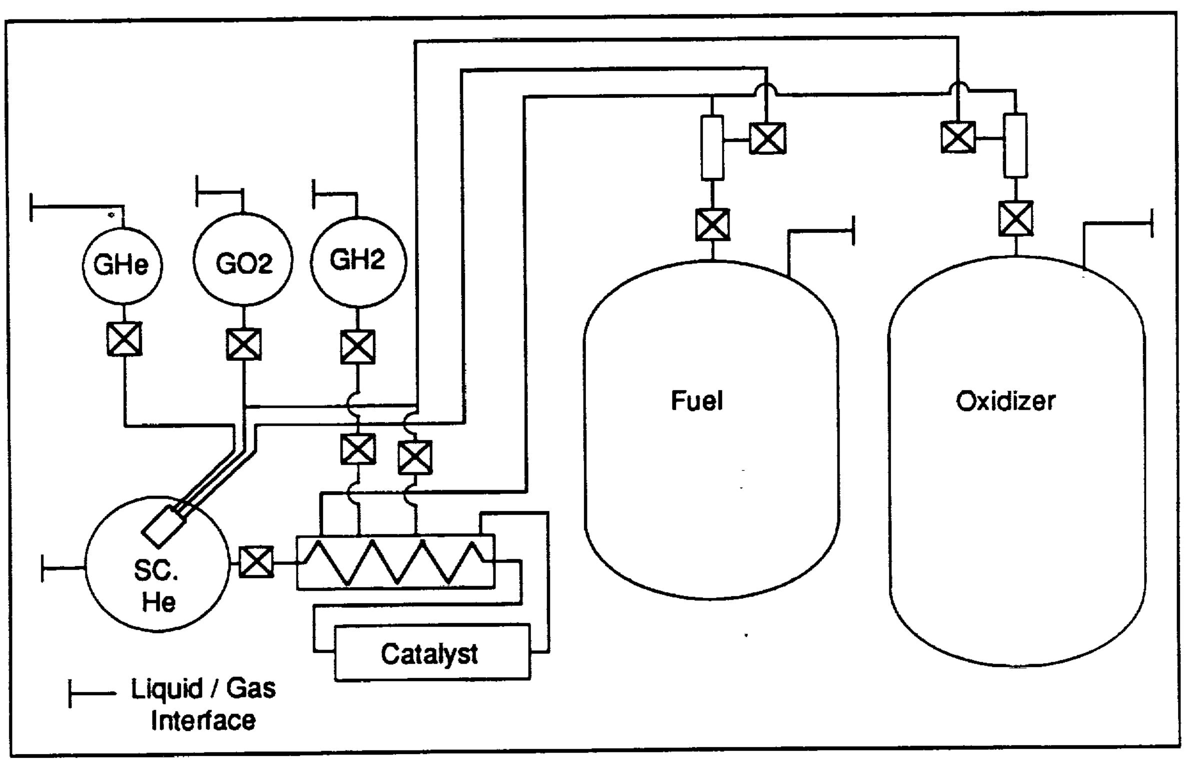


Figure 3.1-9 System 4B: Stored Gas – Catalyst Alternate 2

hydrogen in the cold tank is a viable consideration. This system allows the high density, low temperature storage of the helium, but introduced a new problem, that of catalyst effectiveness at extremely low temperature. Analytical models predicted very low O2/H2 reactivity at inlet temperatures to the catalyst bed over the range of 40-300°R. The system was determined not to be feasible unless the temperature of the catalyst bed was increased to over 300°R.

System 4B – Stored Gas-Catalyst Alternate 2 (Figure 3.1-9) – This system evolved from systems 4 and 4A in an attempt to address the problems posed by the low operating temperatures of the catalyst systems. The system consists of primary and secondary catalyst beds. The catalyst beds are fed from oxygen and hydrogen tanks. The small helium bottle supplies a diluent to the secondary catalyst to prevent it from overheating. Two small catalysts located in the pressurant lines just before the pressurant is introduced into the tanks are called "finishing" catalysts. They are supplied with excess hydrogen at the RP-1 tank and oxygen at the LO2 tank to ensure that no undesired, unreacted species reaches the propellant tanks. Analysis of the maximum concentration of hydrogen in the LO2 ullage or oxygen in the RP-1 ullage subsequently proved that the finishing catalysts were not needed. This system requires more components than other catalyst options but scored well. The heat exchanger required to raise the supercritical helium to temperatures the catalyst can tolerate was scored as a penalty to the system.

System 5 – Stored Gas-Fuel Rich GG (Figure 3.1-10) – This system is similar to system 3 except that the exhaust from the fuel rich gas generator is captured as pressurant for the fuel tank. In order to have the gas generator exhaust to a high-pressure tank ullage, the supply

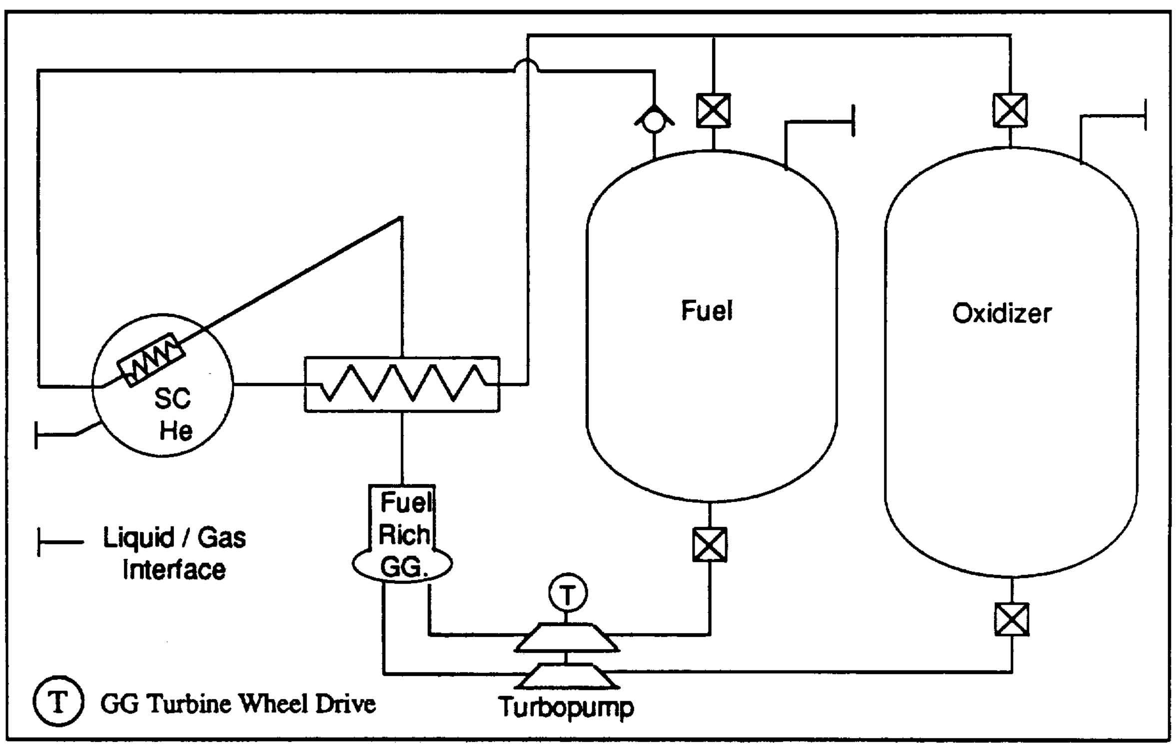


Figure 3.1-10 System 5: Stored Gas – Fuel Rich GG

propellants for the gas generator must be pumped to several hundred psia higher than the tank. The turbopump shown in the schematic is driven by the gas generator discharge. The fuel tank is supplemented with helium from the supercritical tank that supplies pressurant to the oxidizer tank. The inclusion of turbomachinery in the system causes significant reduction in system reliability. This system also results in a high ullage pressurant mass in the fuel tank.

System 6 – Stored Gas-Oxidizer Rich GG (Figure 3.1-11) – Systems 5 and 6 are similar except that an oxidizer rich gas generator is used as the primary heat source and supplemented with helium to pressurize the LO2 tank. Helium is used as the pressurant for the fuel tank. There are no advantages over system 5 because of the high molecular weight of the gas generator exhaust.

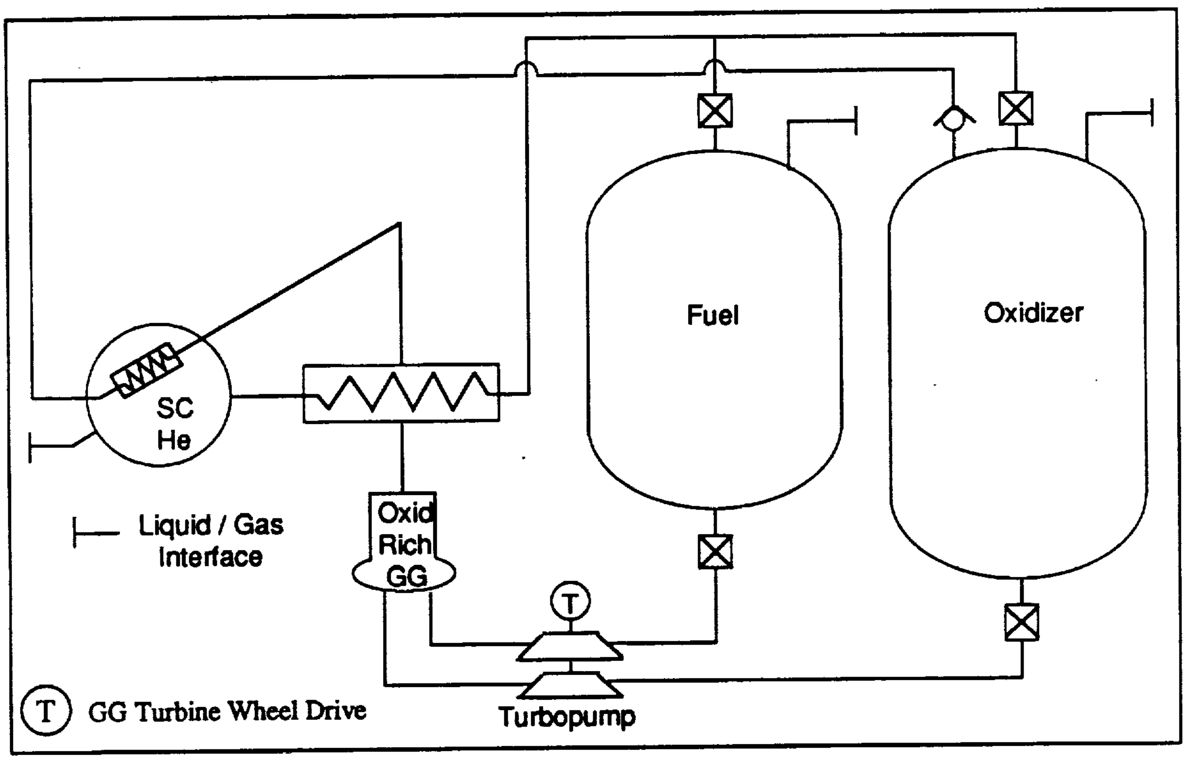


Figure 3.1-11 System 6: Stored Gas – Oxidizer Rich GG

System 7 – Stored Gas Mono Propellant Catalyst (Figure 3.1-12) – This system consists of a hydrazine decomposition catalyst bed primary heat source with a heat exchanger to heat the helium. A heat exchanger in the helium tank is driven on the hot side by the decomposed hydrazine to serve as the secondary heat source. The hydrazine decomposition products are compatible with the RP-1 tank. Helium is required for the oxygen tank. The safety and environmental issues associated with large quantities of hydrazine caused this system to score poorly in the evaluation.

System 8 – Stored Gas - GG Exhaust into Tank (Figure 3.1-13) – This system is a combination of systems 5 and 6. It was included to try to determine if the supercritical helium

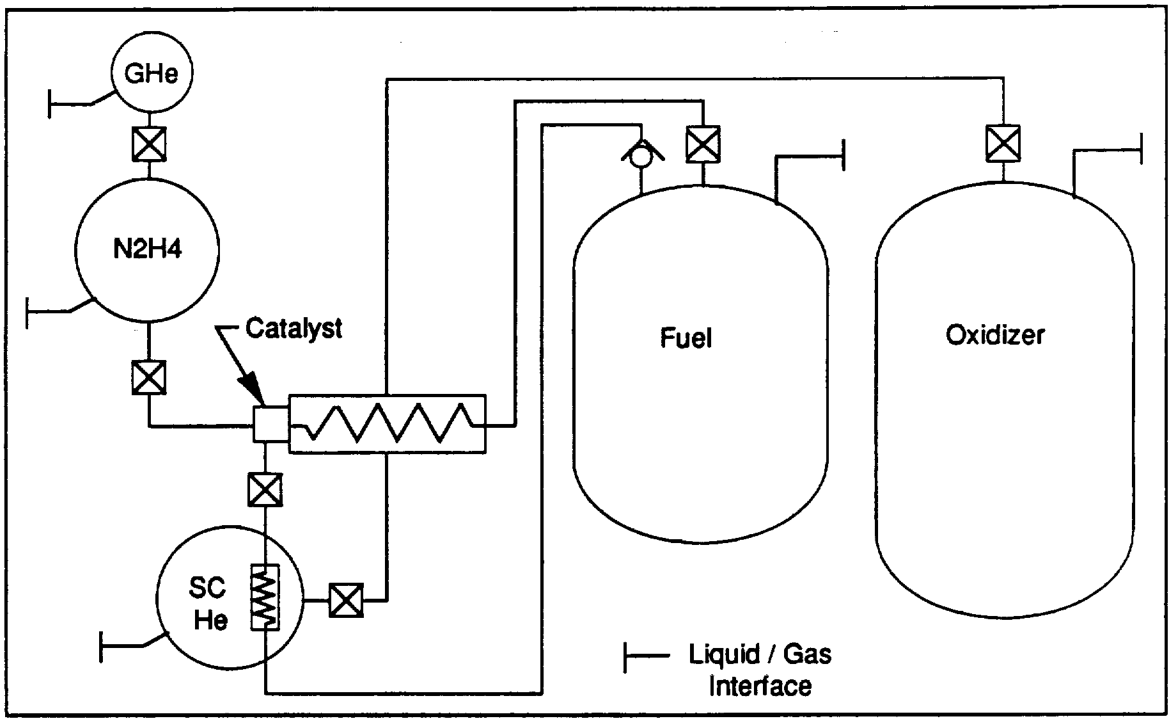


Figure 3.1-12 System 7: Stored Gas – Monopropellant Catalyst

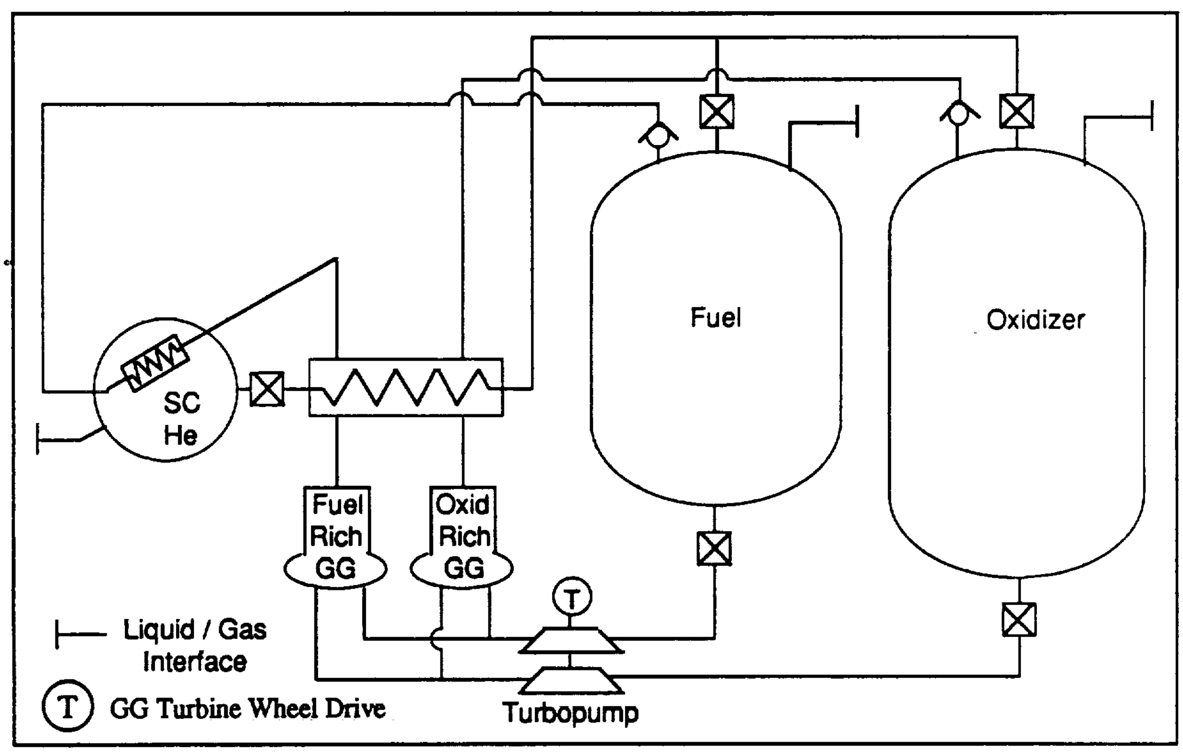


Figure 3.1-13 System 8: Stored Gas – GG Exhaust into Tanks

vessel could be eliminated through the use of gas generators. The resulting highly coupled system still required supplemental helium pressurant to satisfy the range of operation. The turbopump complexity and high weight caused this system to score poorly.

System 9 – Fuel/Oxidizer Rich Solid GG (Figure 3.1-14) – This system consists of two solid gas generators, the exhaust of each compatible with the respective propellant tanks. The system requires the use of particle separators to prevent unburned particles from entering the propellant tanks. The solid propellant evaluation team was unable to determine how to achieve a grain formulation which could meet the temperature and flow rate requirements. The system was therefore classified as not technically achievable.

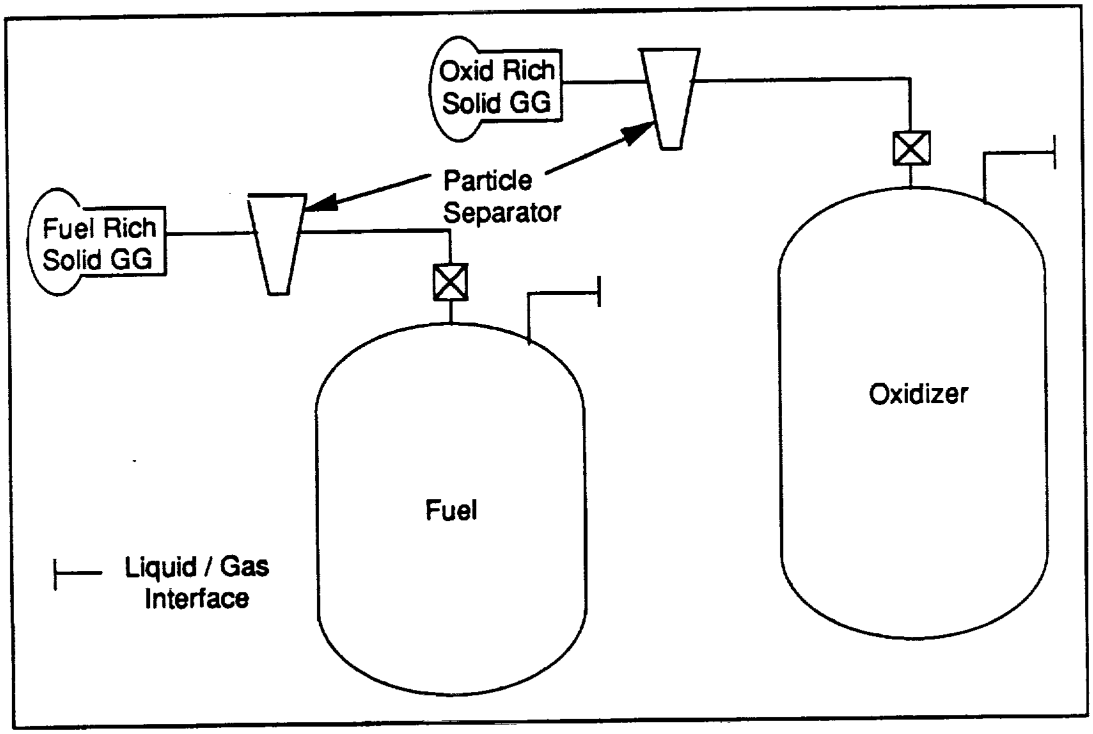


Figure 3.1-14 System 9: Fuel/Oxidizer Rich Solid GG

System 10 – Autogenous LO2/Quasi-Autogenous RP-1 (Figure 3.1-15) – This system uses vaporized oxygen to pressurize the oxidizer tank. The RP-1 propellant does not vaporize without violent decomposition and is therefore unsuitable for this application. Hydrogen is compatible with RP-1 as a pressurant so it was used. A source of vaporized propellant other than from the tank that it pressurizes does not qualify as a true autogenous system, hence the "quasi-autogenous" label. The oxygen tank is handled in a straight autogenous manner. The turbomachinery and the very heavy GO2 ullage (in excess of 98,000 lb) caused this system to score poorly.

System 11 – GG Vaporization Cycle (Figure 3.1-16) – This system uses small combustion chambers with nozzles to vaporize pressurant off the surface of the propellants. The system is considered very difficult to develop and safety considerations prevented further consideration.

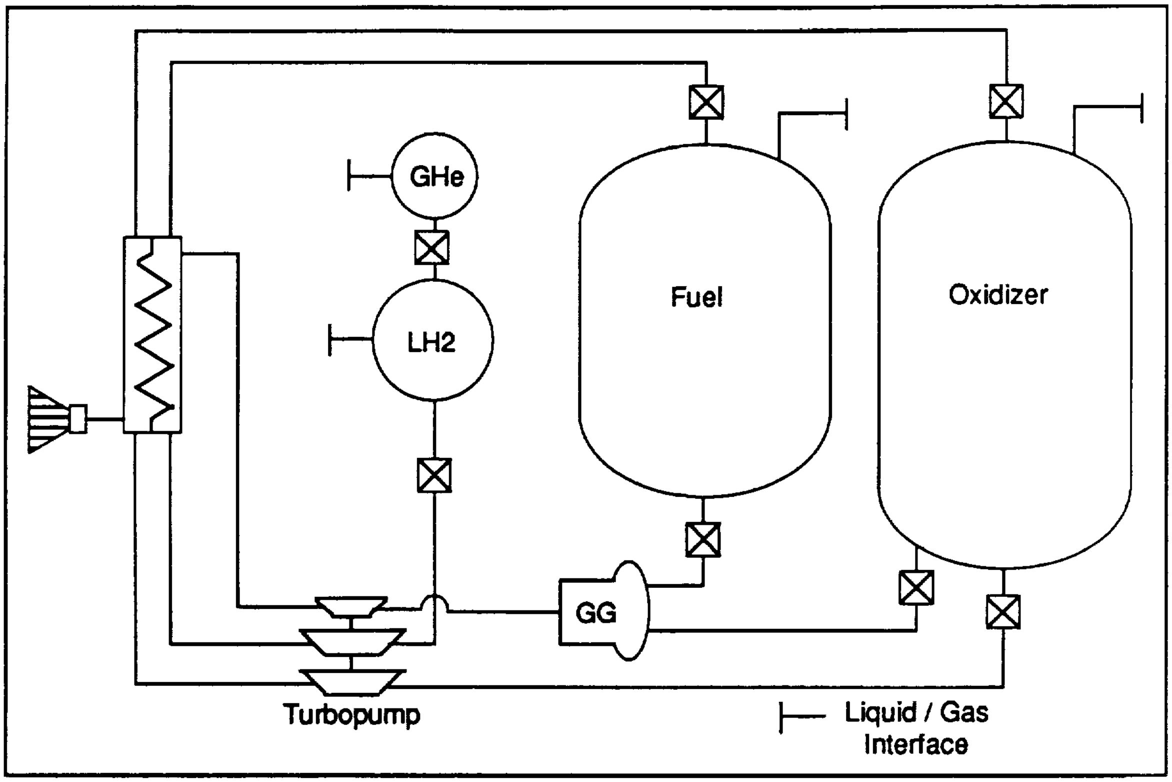


Figure 3.1-15 System 10: Autogenous LO2 – Quasi-autogenous RP-1

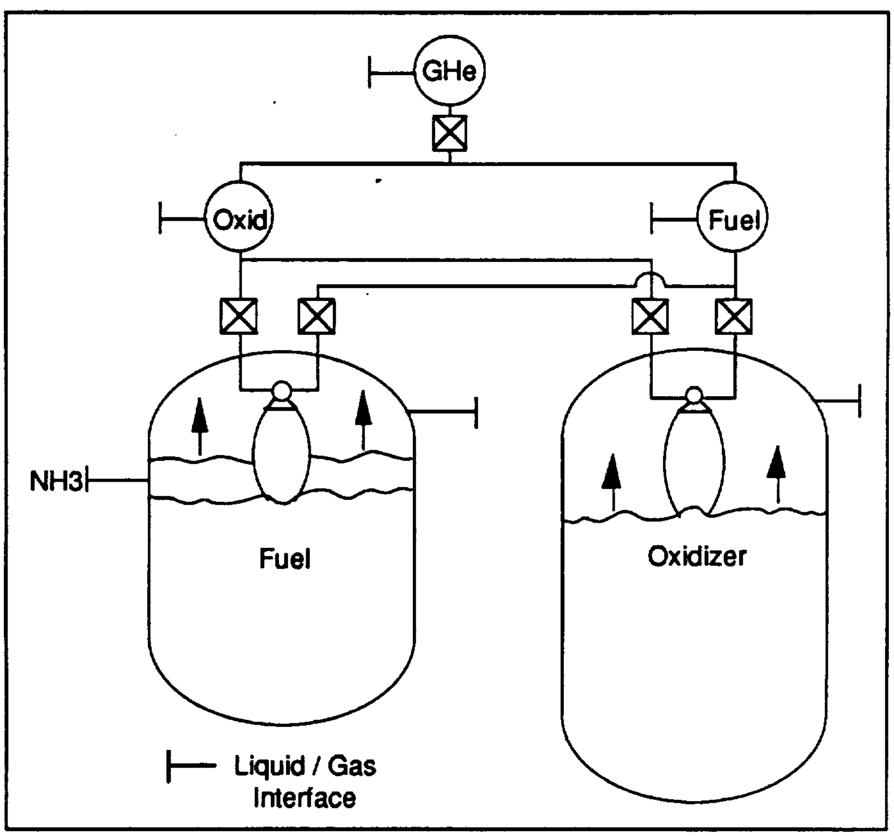


Figure 3.1-16 System 11: GG Vaporization Cycle

System 12 – Direct Tank Injection (Figure 3.1-17) – Direct tank injection (DTI) has been used for propellant tank pressurization on test stands. Hypergolic propellant combinations must be used in order to ensure combustion. The difficulty in employing DTI on an RP-1 tank is that no oxidizer is available which is "aggressive" enough to form a hypergolic combination with RP-1. The use of ammonia floating as a "blanket" on top of RP-1 makes DTI with

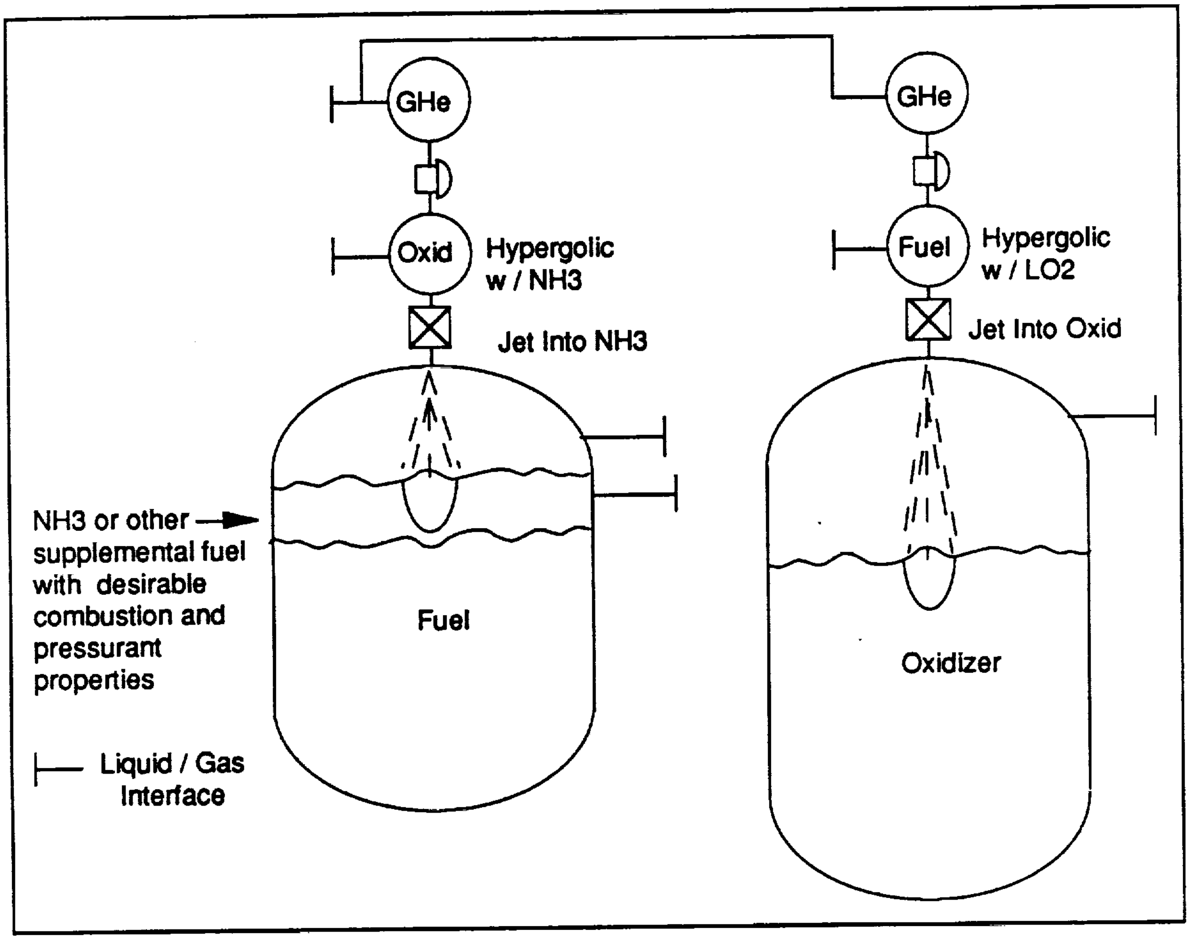


Figure 3.1-17 System 12: Direct Tank Injection

RP-1 possible. Ammonia and RP-1 are not soluble. Ammonia has a lower density than RP-1, and its liquid temperature at atmospheric saturated pressure is several degrees above the freezing point of RP-1. These physical properties can be exploited to allow a hypergolic combination on the surface of the RP-1 tank for pressurization. Safety considerations resulted in the elimination of this system.

3.2 "MUST" CRITERIA SCREENING

Each candidate pressurization system was evaluated against seven "must" criteria as discussed in Section 2.1. Each criterion was evaluated on a go/no go basis. The results of the "must" criteria coarse screen are presented in Table 3.2-1. As shown, six systems passed the "must" criteria screen. Five of these were stored gas systems using stored supercritical

Table 3.2-1 "Must" Criteria Screening

Candidate System	"Must" Criteria						
	Fail-Safe	Verifiable By Test	LO2 & RP-1 Compatible	600-1350 psia	Engine Shut-Down	Booster Integration	Residual Hazards
Stored Gas - Ambient	**No Go**	**Go**	**Go**	**Go**	**Go**	**No Go**	**No Go**
Stored Gas - Steam System	Go	Go	Go	Go	Go	Go	Go
Stored Gas - GG/HX	Go	Go	Go	Go	Go	Go	Go
Stored Gas - Catalyst	Go	Go	Go	Go	Go	Go	Go
Stored Gas - Fuel Rich GG	Go	Go	Go	Go	Go	Go	Go
Stored Gas - Oxid Rich GG	**No Go**	**No Go**	**No Go**	**Go**	**Go**	**Go**	**No Go**
Stored Gas - Monopropellant Catalyst	Go	Go	Go	Go	Go	Go	Go
Fuel & Oxid Rich Liquid GG Exhaust Into Tanks	**No Go**	**No Go**	**No Go**	**Go**	**Go**	**Go**	**No Go**
Fuel & Oxid Rich Solid GG Exhaust Into Tanks	**No Go**	**No Go**	**No Go**	**Go**	**No Go**	**Go**	**No Go**
Autogenous LO2 & Quasi-autogenous RP-1	Go	Go	Go	Go	Go	Go	Go
GG Vaporization Cycle	**No Go**	**No Go**	**No Go**	**Go**	**Go**	**Go**	**No Go**
Direct Tank Injection	**No Go**	**No Go**	**No Go**	**Go**	**Go**	**Go**	**No Go**

($T \approx 40°R$) helium as the pressurant. Each of these options used various methods to provide primary and secondary heat to the helium pressurant. The autogenous LO2/quasi-autogenous RP-1 system also passed the coarse screen. Table 3.2-2 presents the rationale for deletion for the six systems which failed the coarse screen. Details of the coarse screen evaluation are presented in Appendix E of this report.

Table 3.2-2 Rationale for Deletion

Candidate	Failed Criteria	Pro	Con
1 Stored Gas Ambient Helium	Fail-Safe Residual Hazard Vehicle Integration	Least Complex System	High Pressure Hazard - Leaks - Component Design Maturity - Heavy (135,000 lb Tank Weight)
6 Oxidizer Rich GG 8 Oxidizer Rich & Fuel Rich GGs	Fail-Safe Residual Hazard LO2 Compatibility	Lightweight Hardware	- Ingestion of Hydrocarbon Rich Combustion Products into O2 Tank & Pressurization System Violates MSFC-Spec-164A & JSC-SE-S-0073 - Turbopump Required - 92,300 lb O2 Tank Residuals
9 Fuel & Oxidizer Rich Solid GGs	Fail-Safe Residual Hazard No Capability for Cut-off LO2 Compatibility Not Verifiable by Test	Simple System Good Packaging	- Ingestion of Hydrocarbon or Oxygen Rich Combustion Products into Tanks & Pressurization System Violates MSFC-Spec-164A & JSC-SE-S-0073 -145,000 lb of Solid Propellant per Booster - Complex Temp Control Dilution System Required
11 Gas Generator Vaporization Cycle	Fail-Safe Residual Hazard LO2 Compatibility Not Verifiable by Test	Light/Compact Hardware	- Direct Ingestion of Fuel or Oxygen Rich Combustion Products into Propellant Tanks Violates MSFC-Spec-164A & JSC-SE-S-0073 - Injector/Nozzle Contamination can not be Verified by Test (Potential Flame Impingement on Tank Wall)
12 Direct Tank Injection Gas Generator	Fail-Safe Residual Hazard LO2 Compatibility Not Verifiable by Test	Light/Compact Hardware	- High Residual Weight of Pressurant >80,000 lb - Many Technology Issues

3.3 "WANT" CRITERIA SCREENING

The six basic systems that survived the "must" screening were expanded to nine candidates (system options) for the "want" criteria trades. Table 3.3-1 lists these nine trade candidates and summarizes their differences.

Each of the nine candidates was analyzed to develop data used to score the ten different "want" criterion categories. Criteria scores and total weighted scores were calculated for each candidate. A scoring matrix for the nine candidates is shown in Table 3.3-2. System 2A, which is a stored gas system using steam as a helium bottle expulsion source and as a main pressurant heat source,

Table 3.3-1 Pressurization System Fine Screen Candidates

System Number	Stored Pressurant	Primary Heat Source	Secondary Heat Source
2	Supercritical Helium	GG/HX	Steam
2A	Supercritical Helium	Steam	Steam
3	Supercritical Helium	GG/HX	GG/HX
4	Supercritical Helium w/GH2 and GO2	Catalyst	Catalyst
4A	Supercritical Helium	Catalyst	Catalyst
4B	Supercritical Helium	Catalyst	Catalyst/HX
5	Supercritical Helium and Fuel Rich GG Exhaust	GG/HX	GG/HX
7	Supercritical Helium and N2H4 Decomposition	Catalyst/HX	Catalyst/HX
10	LH2 and LO2	GG/HX	N/A

Table 3.3-2 System Trade Studies Scoring Matrix

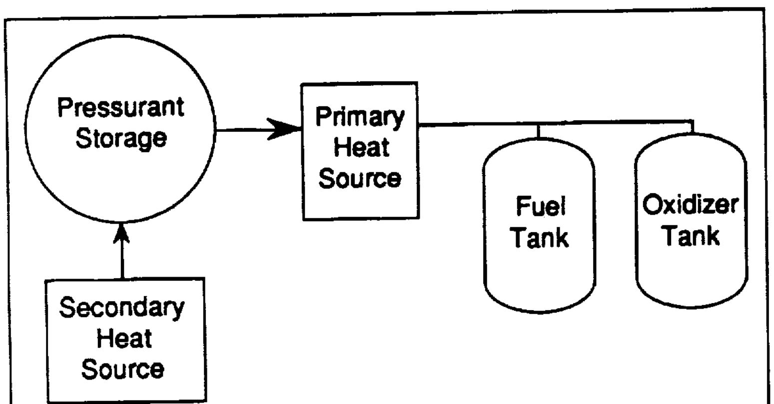
No	Scoring Criteria	Wt.	Cand 2 Stored Gas Steam		Cand 2A Stored Gas Steam		Cand 3 Stored Gas GG/HX		Cand 4 Stored Gas Catalyst		Cand 4A Stored Gas Catalyst Alt.		Cand 4B Stored Gas Catalyst Alt.		Cand 5 Stored Gas Fuel RichGG		Cand 7 Stored Gas Monop Catalyst		Cand 10 Auto LO2 Q-auto RP-1	
			Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc
1	Safety	20	8	160	8	160	9	180	5	100	5	100	5	100	7	140	4	80	7	140
2	Reliability	20	7	140	10	200	8	160	6	120	5	100	4	80	2	40	6	120	1	20
3	System Packaging	10	9	90	10	100	9	90	3	30	6	60	7	70	8	80	6	60	6	60
4	Weight	5	6	30	10	50	6	30	4	20	7	35	8	40	7	35	5	25	3	15
5	Supportability	5	8	40	6	30	10	50	1	5	1	5	1	5	5	25	3	15	2	10
6	System Performance (Control Complexity)	10	8	80	10	100	9	90	9	90	9	90	7	70	6	60	9	90	8	80
7	Operational Complexity (Ground Ops)	5	10	50	10	50	10	50	5	25	6	30	6	30	9	45	6	30	9	45
8	Technology Needs	5	6	30	6	30	9	45	8	40	8	40	4	20	6	30	5	25	10	50
9	Development Risk	5	7	35	6	30	10	50	8	40	8	40	5	25	6	30	5	25	8	40
10	Cost - LCC	15	4	60	10	150	3	45	1	15	7	105	8	120	3	45	1	15	1	15
	Total	100																		
	Weighted Score			715		900		790		485		605		560		530		485		475
	Rank			3		*1		2		6			4			5			6	
	Rank-Less 2A			2				1		5			3			4			5	

* Based on incomplete Thermophysical Properties of Steam at Critical Point

was the leading trade candidate. However, consultation with the NBS and subsequent analyses indicated that properties of steam assumed in the evaluation were unsupported. Preliminary communication with the NBS on the effects of mixing steam near its critical point with helium led to the conclusion that the apparent "excess" enthalpy encountered upon mixing would yield a higher temperature than the approach considering the classical mixed enthalpy of the combined fluid stream. After a more detailed examination of the literature and consultation with specialists in the field, it was determined that the "excess" enthalpy comes about from an increase in density, not an increase in temperature. When the system was resized to account for the correct mixing properties, the resized system was too large and heavy to warrant further consideration, and was therefore dropped. The large amount of water introduced into the propellant tanks also detracted from this system. It was therefore recommended that systems 2 and 3, (stored gas with gas generators and heat exchangers as a primary heating source) and systems 4A and 4B (stored gas with catalyst beds as a primary heat source), be carried forward into the system optimization and down-select phase of the PTPSTP studies. Additional details of the "want" criteria screening are contained in Appendix E of this report.

3.4 SELECTED SYSTEM OPTIMIZATION AND FINAL DOWN-SELECT

The systems selected for optimization are common in that all store the helium pressurant at supercritical temperature (40°R) and 3000 psia, use secondary heating to expel the pressurant from the storage dewar, and have primary heat sources to expand the helium before introducing the pressurant into the propellant tanks. The difference between selected systems is the method used to heat the helium pressurant (Figure 3.4-1).



Primary Heat Source Options	Secondary Heat Source Options
Gas Generator/Heat Exchanger	Steam
Catalyst Bed	Recirculation Helium
O2/H2 Helium Heater	Catalyst Bed-Tridyne
	O2/H2 Helium Heater

Figure 3.4-1 Primary and Secondary Options to Heat Helium Pressurant

An O2/H2 helium heater performs the same function as a catalyst bed by using stoichiometric combustion of O2 and H2 instead of catalytic combination of O2 and H2 to heat the pressurant helium. This option was added to the optimization study after recommendation by MSFC and evaluation by Martin Marietta and Aerojet.

An assessment of the selected primary/secondary heating options produced six system optimization candidates for further study and final candidate selection. Schematics of these candi-

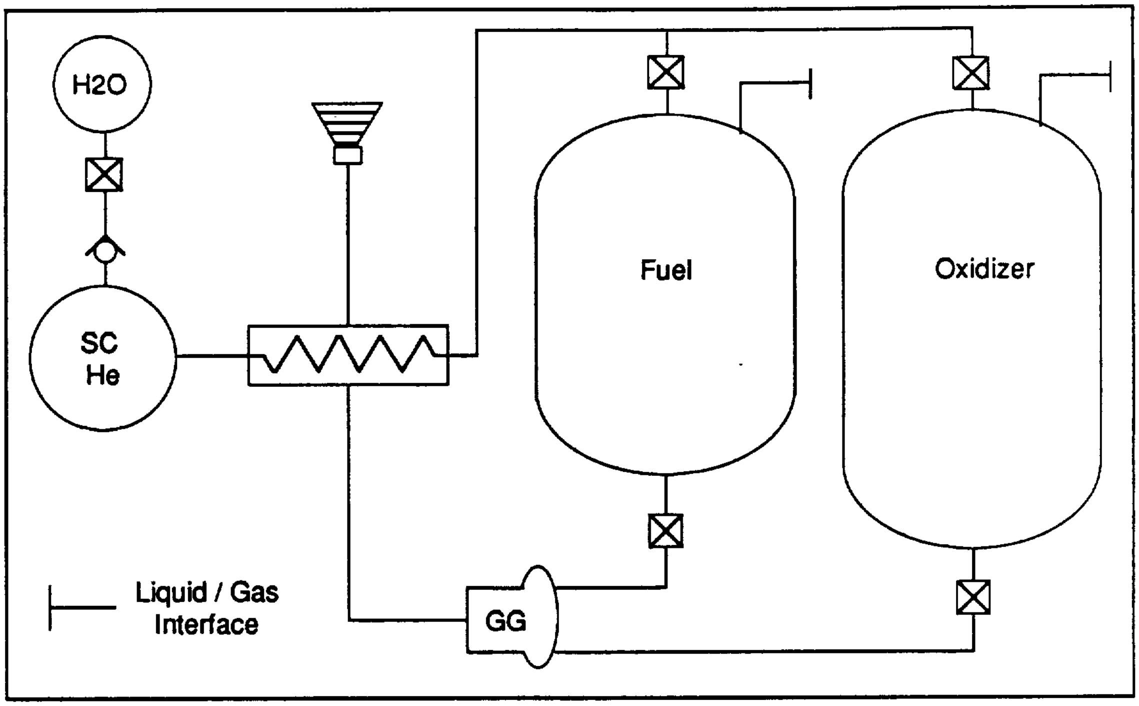


Figure 3.4-2 Optimization Candidate 1 – GG/HX/Steam

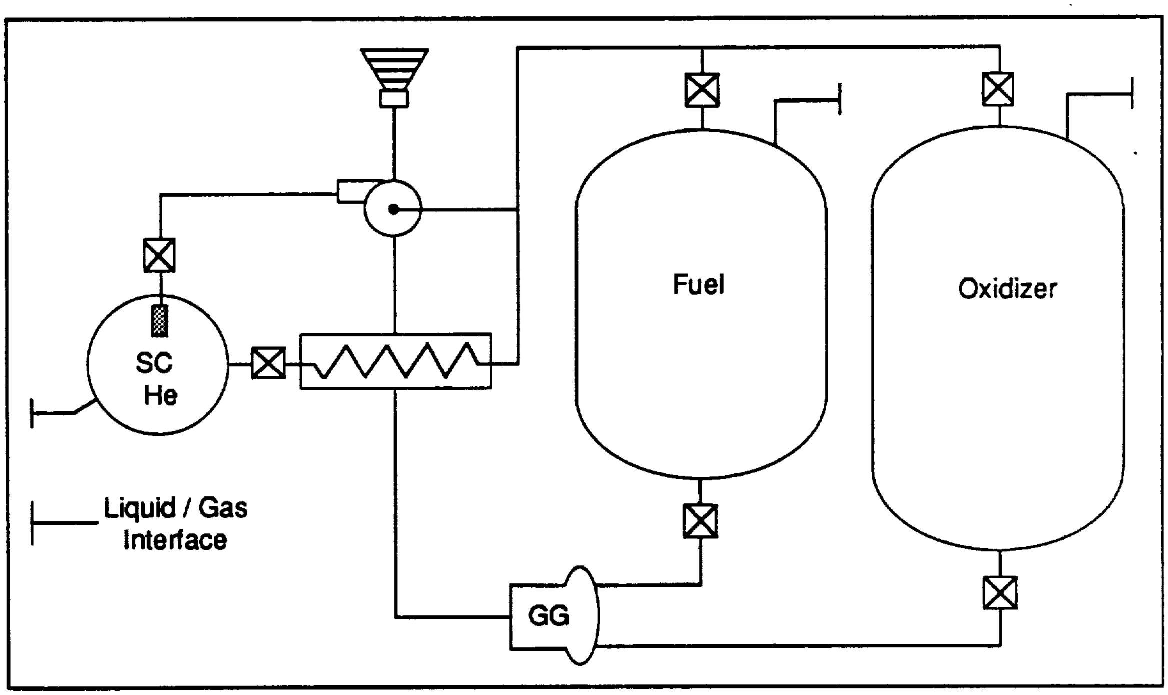


Figure 3.4-3 Optimization Candidate 2 – GG/HX

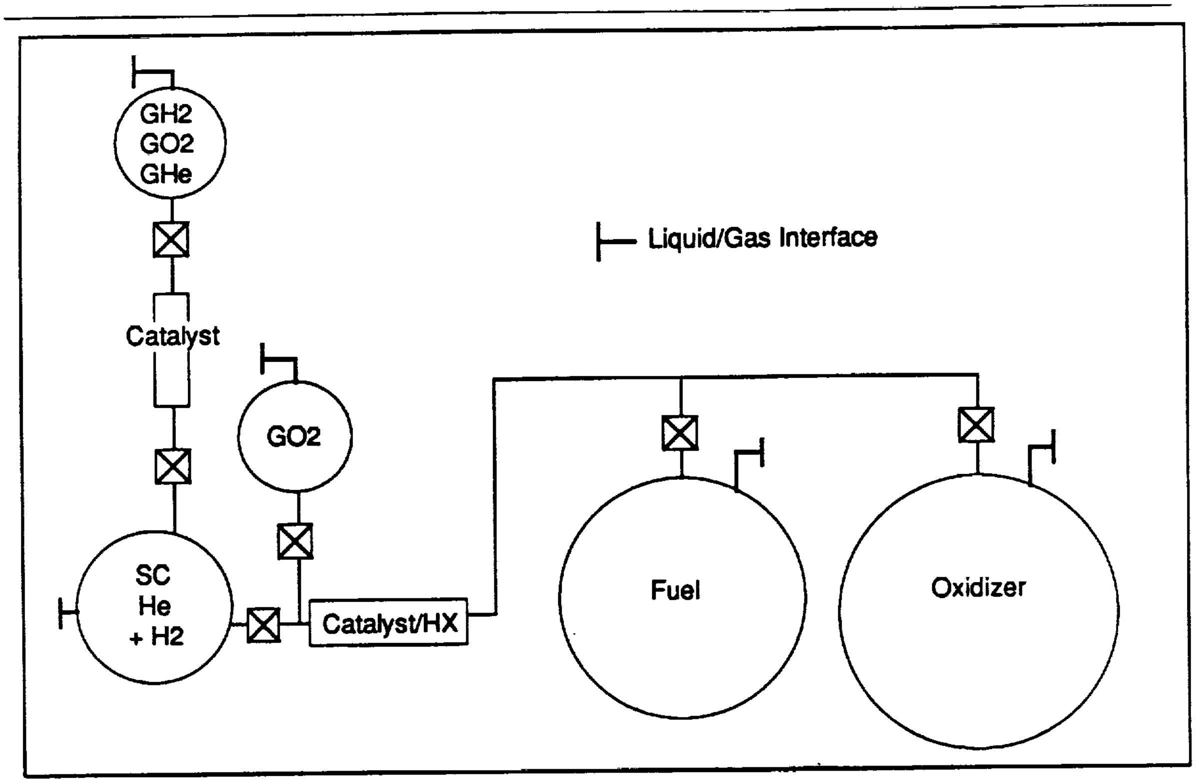


Figure 3.4-4 Optimzation Candidate 3 – Catalyst Alternate

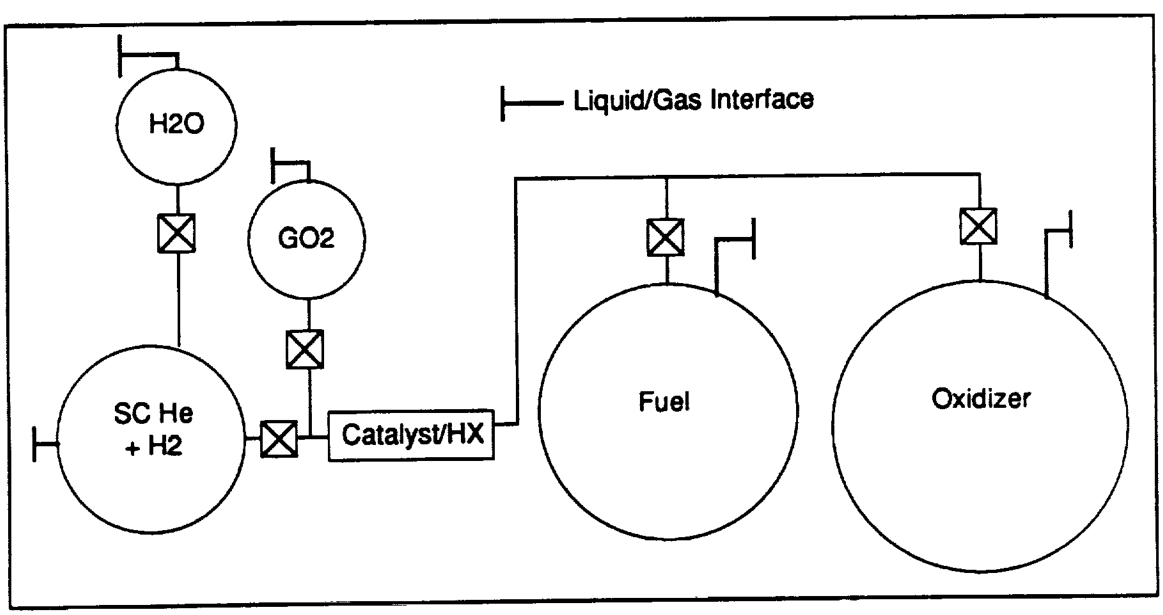


Figure 3.4-5 Optimization Candidate 4 – Catalyst Alternate/Steam

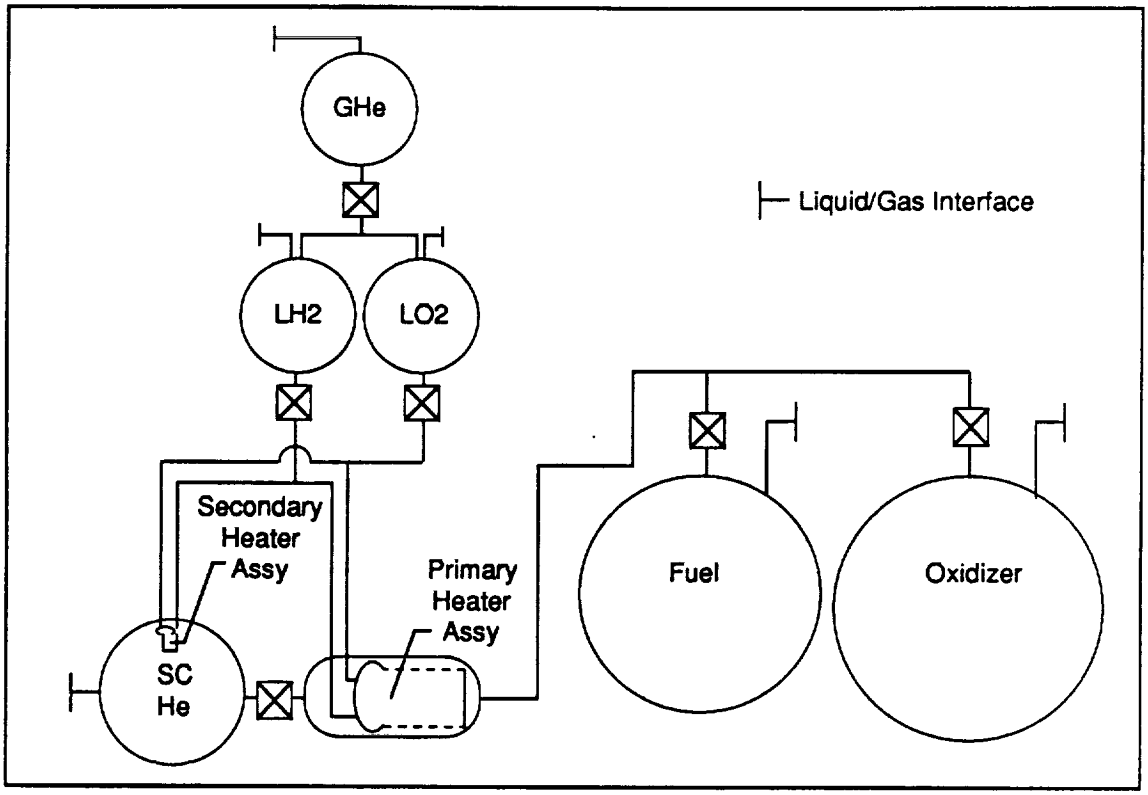


Figure 3.4-6 Optimization Candidate 5 – LO2/LH2/He Heater

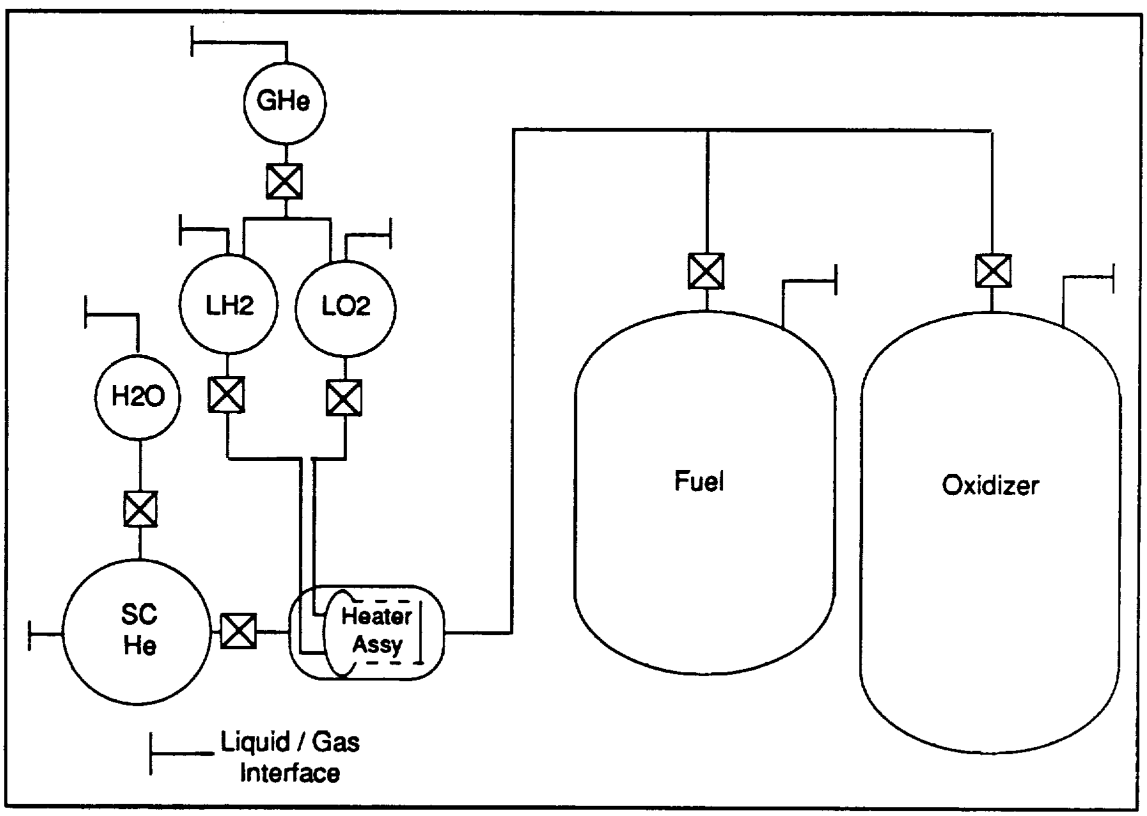


Figure 3.4-7 Optimization Candidate 6 – LO2/LH2/He Heater/Steam

dates are shown in Figures 3.4-2 through 3.4-7. Optimization of the candidates was accomplished by applying common system design goals to each. Optimization goals were developed for seven categories as presented in Table 3.4-1. As can be seen, some optimization goals were common to several categories. Each system design was analyzed and modified in both system design and vehicle packaging to satisfy as many optimization goals as possible.

Table 3.4-1 Pressurization System Optimization Goals

1 Safety
- • Reduce number of high-pressure bottles

2 Reliability
- • Reduce number of components
- Eliminate single failure points, except structure, pressure vessels
- Hardware single fault tolerant
- Separate redundant systems
- Separate/isolate incompatible systems, materials, environments
- Provide redundancy verification, monitoring, management

3 Supportability
- • Design for easy component removal
- Use standardized components and subsystems
- Use "off-the-shelf" components
- Minimize GSE/TSE
- • Lower checkout/test and calibration requirements
- • Reduce number of components

4 Ground operations
- Ignition system minimizing last minute access and servicing
- Uniform TPS thickness
- Minimize launch site TPS closeouts
- Minimize attach points in TPS areas
- • Reduce number of components
- • Reduce launch site checkout
- • Easy access to components
- Locate umbilicals to facilitate loading
- Use automated/BITE checkout

5 Packaging
- • Reduce number of components
- Reduce size/weight of components
- Provide additional I/T or forward skirt volume
- Reduce number of valves/sizes
- Minimize external line runs & protuberances
- Minimize large diameter flex lines & high-pressure bellows
- Minimize dewar penetrations & internal components
- Minimize ground umbilicals

6 Cost
- • Reduce number of small tanks

7 Controls
- Reduce number of control loops
- Reduce instrumentation and number of sensors
- Simplify startup/shutdown procedures
- Eliminate special startup/shutdown hardware

• Multi-discipline requirement

The six optimized system candidates were then compared using the standard Martin Marietta trade study methodology to select the best flight system. Each system was analyzed with respect to 10 scoring criteria and comparative scores developed. The criteria scores and weighted scores are shown in Table 3.4-2. This scoring matrix can also be presented in a more subjective manner as shown in Table 3.4-3. Table 3.4-4 summarizes the results of the trade analyses for the six optimized system candidates.

The two highest scoring systems, 4 and 5, were subjected to a risk assessment, and the relative risk to successfully develop each system was compared. The risk assessment indicated that system 5 was the best overall choice for the flight pressurization system. The summary results of the risk assessment are shown in Table 3.4-5.

A weighting factor sensitivity assessment was also performed to evaluate the impact of weighting factor values on trade study results. The

Table 3.4-2 System Optimization Scoring Matrix

No.	Scoring Criteria	Wt.	Cand 1 GG/HX/ Steam		Cand 2 GG/HX		Cand 3 Catalyst Alternate		Cand 4 Catalyst Alternate/ Steam		Cand 5 LO2/LH2/ He Heater		Cand 6 LO2/LH2/ He Heater/ Steam	
			Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc	Sc	Wt. Sc
1	Safety	20	10	200	9	180	8	160	9	180	8	160	8	160
2	Reliability	20	10	200	1	20	8	160	9	180	7	140	7	140
3	System Packaging	10	5	50	4	40	8	80	8	80	10	100	9	90
4	Weight	5	2	10	2	10	7	35	8	40	10	50	10	50
5	Supportability	5	10	50	8	40	8	40	8	40	7	35	7	35
6	System Performance (Control Complexity)	10	10	100	10	100	9	90	9	90	9	90	9	90
7	Operational Complexity (Ground Ops)	5	10	50	9	45	5	25	8	40	10	50	8	40
8	Technology Needs	5	8	40	9	45	9	45	8	40	10	50	9	45
9	Development Risk	5	8	40	10	50	9	45	8	40	10	50	9	45
10	Cost - LCC	15	4	60	1	15	10	150	10	150	10	150	10	150
	Total	100												
	Weighted Score			800		545		830		880		875		845
	Rank			5		6		4		2		1*		3

* Based on Risk Assessment

Table 3.4-3 System Optimization Results

No	Evaluation Criteria	Cand 1 GG/HX/ Steam	Cand 2 GG/HX	Cand 3 Catalyst Alternate	Cand 4 Catalyst Alternate/ Steam	Cand 5 LO2/LH2/ He Heater	Cand 6 LO2/LH2/ He Heater/ Steam
1	Safety	O	O	E	O	E	E
2	Reliability	O	M	E	O	E	E
3	System Packaging	M	M	E	E	O	O
4	Weight	M	M	G	G	O	O
5	Supportability	O	G	G	G	G	G
6	System Performance (Control Complexity)	O	O	E	E	E	E
7	Operational Complexity (Ground Ops)	O	E	M	G	O	G
8	Technology Needs	G	E	E	G	O	E
9	Development Risk	G	O	E	G	O	E
10	Cost - LCC						
	Overall Concept Evaluation	G	M	G	E	O	G

O - Outstanding E - Excellent G - Good M -Marginal

Table 3.4-4 Candidate Scoring Summary

Candidate	Advantages	Disadvantages	Rank
1 GG/HX/Steam	High Safety/Reliability Easy Support Easy Control Simple Operations	High Weight High Cost Hard to Package	5
2 GG/HX	High Safety Easy Control Low Technology Needs Low Development Risk Simple Operations	High Weight High Cost Low Reliability Hard to Package	6
3 Catalyst Alternate	High Safety/Reliability Easy Control Low Development Risk Low Technology Needs	Difficult Ground Ops	4
4 Catalyst Alternate/Steam	High Reliability Easy Control Low Cost		2
5 LO2/LH2/He Heater	High Safety/Reliability Low Weight Easy to Package Low Technology Needs Low Development Risks Simple Operations Low Cost		1
6 LO2/LH2/He Heater/Steam	High Safety/Reliability Easy to Package Low Weight Easy Control Low Technology Needs Low Development Risk Low Cost		3

weighting factors were adjusted into four groups: 1) high safety weight, low operations weight (values used in trade); 2) balanced weight with 25%/group; 3) balanced weight with 10%/criteria; and 4) high operations and performance weight, low cost/risk weight, medium safety weight. Table 3.4-6 presents the weighting factor sensitivity assessment results and comparative scores for systems 2, 4, and 5. These results, plotted in Figure 3.4-8, show that adjustments to the trade study weighting factors from the baseline improves the ranking of system 5 relative to the other candidates. The selection of system 5 is, therefore, supported by this assessment.

The rationale for the selection of a system which uses helium heater(s) as the best flight pressurization system energy source is summarized in the following paragraphs:

Table 3.4-5 LO2/LH2/He Heater vs Catalyst Alternate/Steam Risk Assessment

Water/Ice Management
- Heater is Lower Risk
  - 80 % Less Steam in Dewar as Compared to System 4
- Heater is More Tolerant of Ice Crystals

Technical/Development Risk
- Heater is Lower Risk
  - Utilizes Existing Technologies
  - Catalyst Startup at Low Temperatures Issues Are Unresolved

System Flexibility Assessment
- Heater Provides More Flexibility for Varying Operating Conditions
  - Liquid vs Gas Supply
  - Stratified vs Unstratified Dewar Conditions
  - Does Not Require Gas Mix in Dewar
- System Can be Optimized with a Heater on PTF
- Catalyst Can be Developed to Point Design Requirements and Tested on PTF
  - Simple PTF Change

Selected System Is LO2/LH2/He Heater

Table 3.4-6 "Want" Criteria Weighting Factor Sensitivity Assessment

Scoring Criteria	As Proposed High Safety Low Operations		Balanced 25% Group		Balanced 10% Each		High Operations High Performance Low Cost/Risk Medium Safety	
Safety Reliability	20 20	40%	12.5 12.5	25%	10 10	20%	10 10	20%
Operational Complexity Supportability	5 5	10%	12.5 12.5	25%	10 10	20%	17.5 17.5	35%
Weight Packaging System Performance	5 10 10	25%	5 10 10	25%	10 10 10	30%	15 10 10	35%
Technology Needs Development Risk Development Cost	5 5 15	25%	5 5 15	25%	10 10 10	30%	5 5 5	15%
Selected System's Scores 4 5 1	 880 875 800		 865 891 800		 850 910 770		 880 938 830	

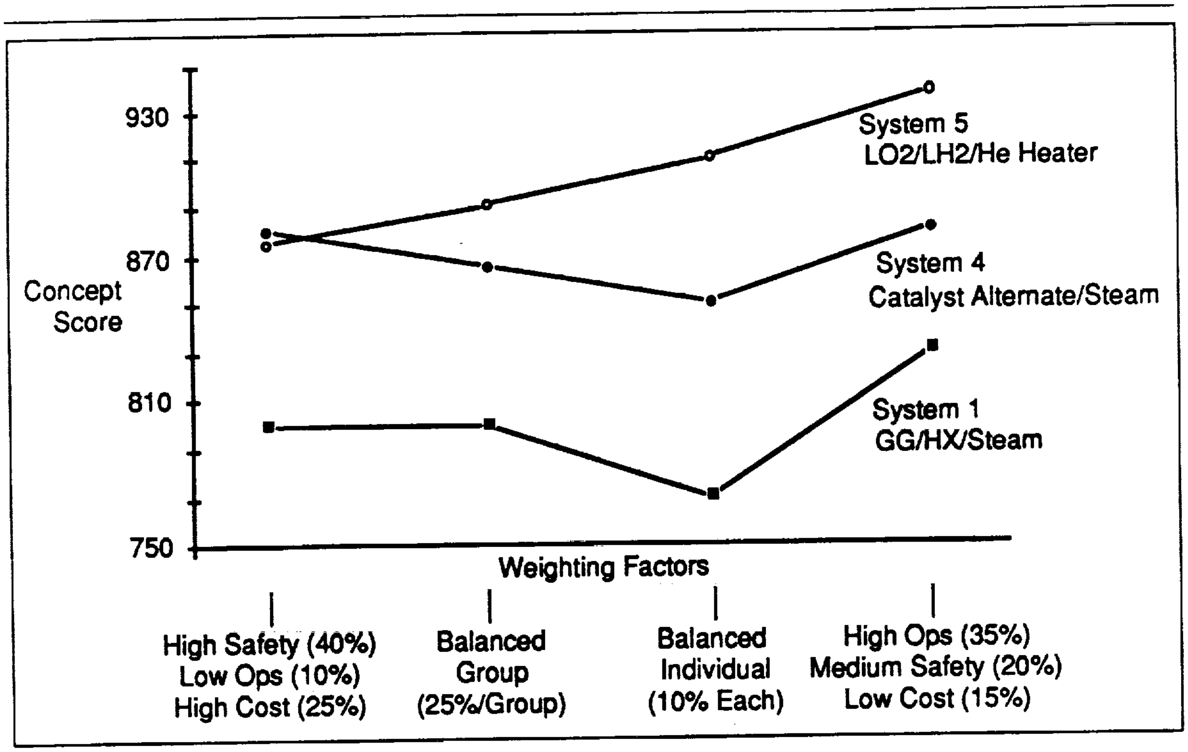


Figure 3.4-8 "Want" Criteria Weighting Factor

Safety - The heater is a simple component and is functionally reliable. In addition, any non-combusted propellants in the helium heater cannot exceed flammability limits in the pressurant gas. Worst case would have the hydrogen and oxygen propellants mixing with the helium flow through the heater without any combustion. This would provide a pressurant mixture by volume of 94.3% helium, 3.8% hydrogen, and 1.9% oxygen. This ratio is below the O2/H2 flammability limit shown in Figure 3.4-9. Overall this system has an excellent safety rating.

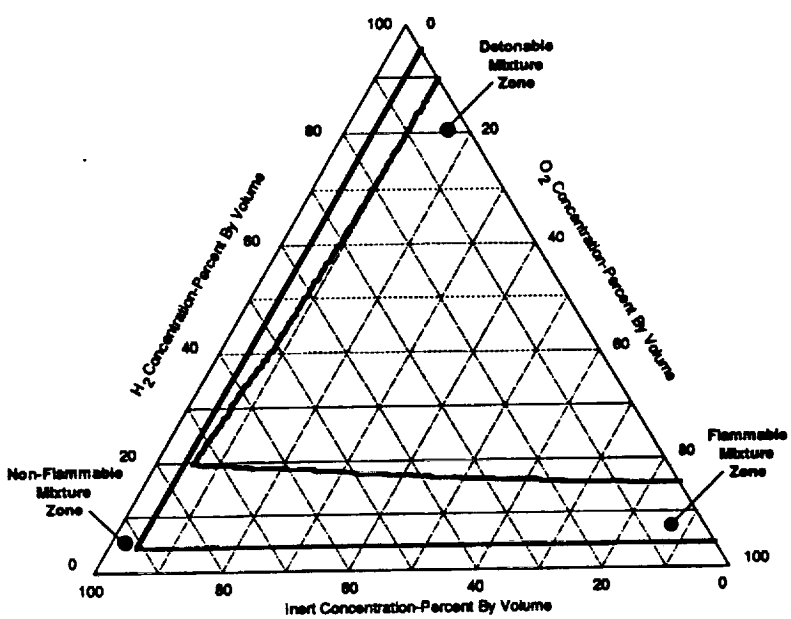


Figure 3.4-9 Experimentally Verified O2/H2/Inert Combustion Domain

Reliability - There are no functional criticality 1 failure modes in system 5. The system is fully redundant. Reliability is negatively impacted by control system complexity and the existence of 92 criticality 1 structural failure modes. It can be seen from structural criticality 1 count, shown in Table 3.4-7, that the selected system has slightly more criticality 1 failure modes than competing systems but is still considered an excellent system from a reliability standpoint.

System Packaging - The selected system packages better than other systems because of smaller components and shorter line lengths. All components fit in the LRB forward skirt and nose cone volume. Packaging is compromised somewhat by the need for four pressurized

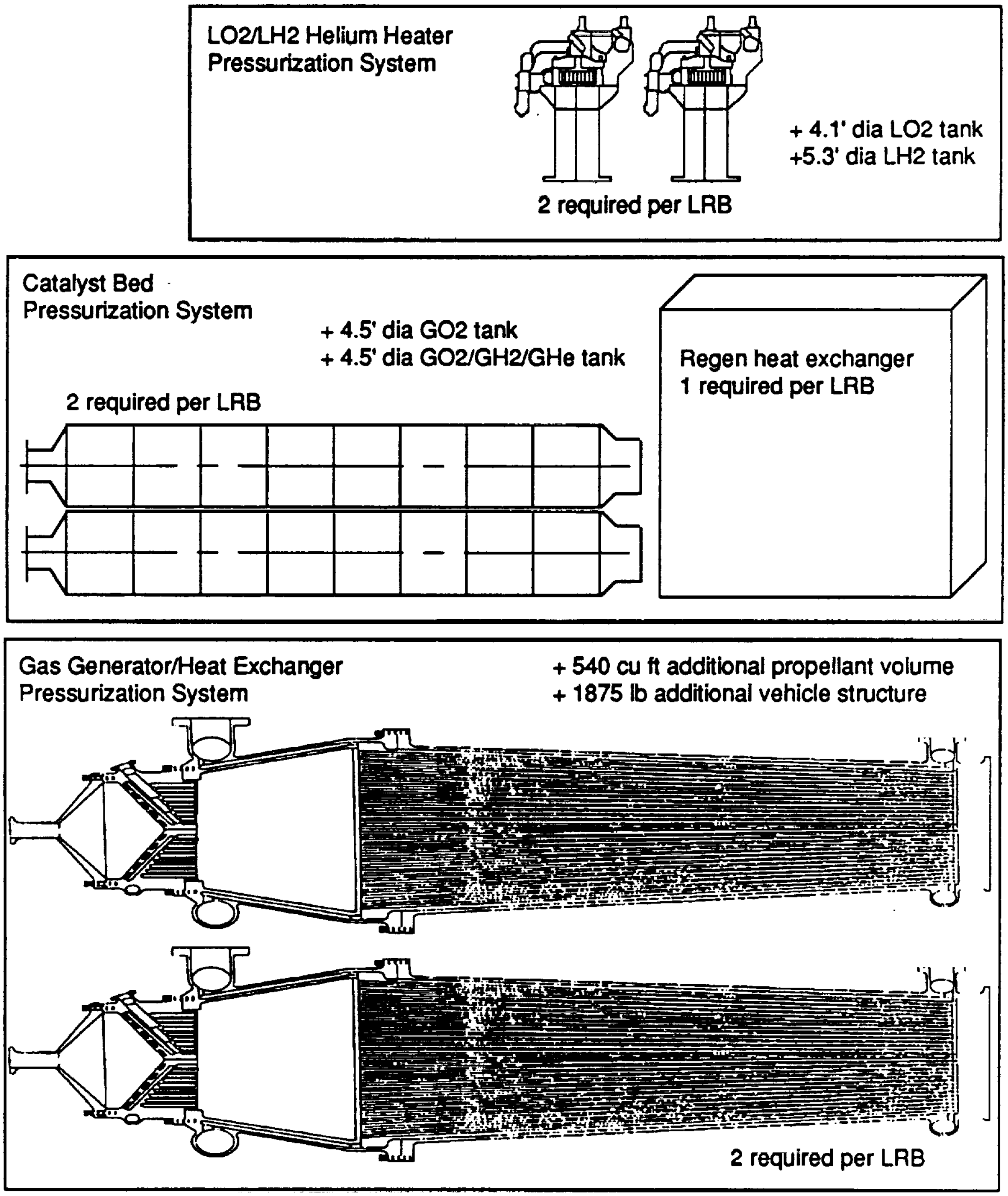


Figure 3.4-10 Relative Size of Primary Heat Source

storage vessels. This system is rated outstanding for packaging in an LRB size vehicle. Figure 3.4-10 shows the relative size of key components for the heater, catalyst bed and gas generator/heat exchanger systems. The advantage of the heater system size is obvious.

Weight - The selected helium heater system has the lowest system weight of all of the studied systems. Most of its components are small, providing an LRB size system weight of 39,200 lb. This compares to 51,900 lb for a catalyst system and 70,300 lb for a gas generator/heat exchanger system. The selected system was rated outstanding from a weight standpoint.

Supportability - Supportability was a category where the selected system scored lower than a competing system. Although it has small components, the system has 138 LRUs. The overall rating of the system in this category was good.

System Performance (Control Complexity) - The selected pressurization system has a simple control system and was rated best in terms of control authority and control flexibility. The system has only four control loops, but is degraded by increased instrumentation requirements. Fourteen sensor sets are required. Overall the system is rated excellent in the system performance category.

Operational Complexity (Ground Ops) - System 5 is considered to have minimum ground operations requirements and complexity when compared to the competing systems. The only detracting factors are four heater units which must be processed and four tanks which must be loaded. The system is rated outstanding for ground operations. Large cryogenic helium conditioning equipment is needed by all of the systems studied and is not considered a discriminator between systems.

Technology Needs/Development Risk - These evaluation criteria are directly related. The more technology needs, the higher the development risk. Technology needs for the selected system are modest. Small amounts of water in the system must be accommodated, and the system is considered tolerant to small amounts of ice. The primary heater and its ignition in a cryogenic environment is the main technology issue. Because of Aerojet IR&D demonstrations of similar hardware, an established technical database exists. The selected system is rated outstanding in these categories.

Cost - System 5 is the lowest cost system of those studied. It has one of the lowest life cycle costs, $812.5M, and the lowest DDT&E cost, $9.5M. It is rated outstanding in the cost category.

The selected helium heater pressurization system was rated as good as, or better than, the other competing systems in all the selection rationale categories with one exception. It was slightly inferior in the category of supportability. Table 3.4-8 summarizes the selection rationale discussed above. This table shows that while it was essentially equal to gas generator/heat exchanger and catalyst systems in the areas of safety and reliability, its superiority in the areas of system size, weight and cost make the O2/H2 helium heater system the preferred option for an LRB/HRB propellant tank pressurization system.

Table 3.4-8 Final Selection Data Summary

	GG/HX	Catalyst	LH2/LO2 He Heater
Packaging	Size, weight, line length	Size, weight	
Safety Concerns	GG over temp GG coking	Catalyst contamination	System complexity
Reliability	No non-redundant functional crit 1 failures	No non-redundant functional crit 1 failures	No non-redundant functional crit 1 failures
Life Cycle Costs	$1,219M	$851M	$813M
Weight	70,000 lb	52,000 lb	39,000 lb
Technology Cost	High	High	Medium

Table 3.4-9 System Reference Number Cross Reference

Optimization System Candidate Reference Number (Vol II)	System Candidate Reference Number (Appendices)
1 GG/HX/Steam	2
2 GG/HX	3
3 Catalyst Alternate	4A
4 Catalyst Alternate/Steam	4A-2
5 LO2/LH2/He Heater	4Z
6 LO2/LH2/He Heater/Steam	4Z-1

Detailed selection methodology and candidate systems data, such as weight breakdown and component sizes, are presented in appendices E and F of this report. Table 3.4-9 presents a cross reference between optimization candidate systems reference numbers and candidate reference numbers in the appendices.

4.0 SELECTED SYSTEM DEFINITION

4.1 SYSTEM DESCRIPTION

The flight pressurization system selected with the optimization studies is a stored pressurant gas system using O2/H2 fueled helium heaters for both the primary and secondary heat sources. The helium pressurant is stored as a supercritical fluid at 3000 psia and 37-40°R. This takes advantage of the relatively high density of the helium at these conditions. The primary heat source is an LO2/LH2 fueled helium heater. The oxygen and hydrogen burn at near stoichiometric conditions (O/F ≈ 8) and mix with the cold helium pressurant to produce an ullage pressurant gas at 900-1000°R. The O2/H2 secondary heater is also a stoichiometric burner which exhausts into the helium storage dewar to provide the energy for positive dewar expulsion over the complete system duty cycle. Both heaters are supplied by a pressure-fed LO2/LH2 system. Ambient helium at 4000 psia pressurizes the LO2 and LH2 tanks. A simplified schematic of the system is shown in Figure 4.1-1. Figure 4.1-2 is a more detailed system schematic that presents flow rates, temperatures, and pressures in the system as well

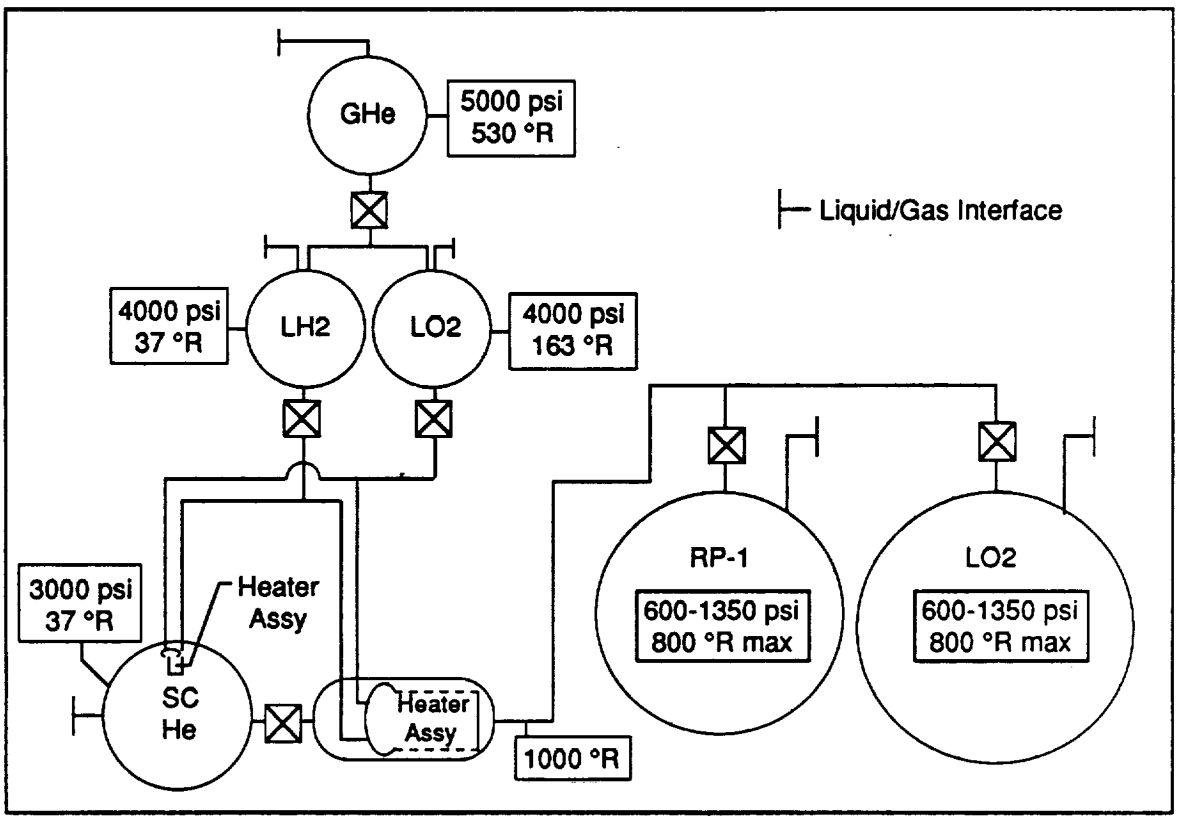
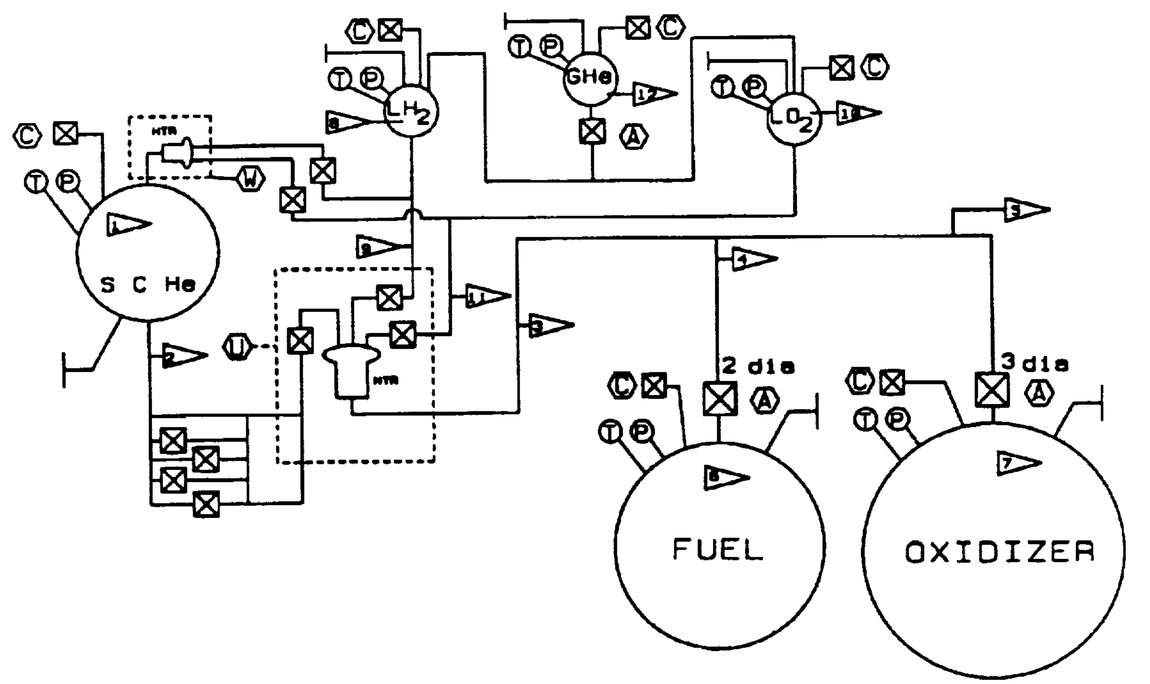


Figure 4.1-1 PTPSTP Selected System LO2/LH2/He Heater

as the sizes of major hardware components and the number of control components in the system. The system has been sized to be consistent with the requirements presented in Section 1.2 of this volume.

The system components are relatively small with the exception of the main helium storage dewar and package well into an LRB size vehicle. Most system components are



XX	$\dot{m}$ lb/sec max	P psia	T °R	M lb	ø
1	—	3000	40	14325	13 ft
2	155	3000	40	—	3 in
3	155	1500	1000	—	5 in
4	55	1500	1000	—	2 in
5	100	1500	1000	—	3 in
6	—	1350	1000	—	—
7	—	1350	1000	—	—
8	—	4000	37	325	5.3 ft
9	3.5	4000	37		2 in
10	—	4000	163	2585	4.1 ft
11	28.5	4000	163	—	2 in
12	—	5000	500	400	6.3 ft

COMPONENT	size ø in.	QTY
2 WAY VALVE	.5 2 3	2 26 6
	TOTAL	34
PRESSURE RELIEF VALVE	TOTAL	12
CHECK VALVE	TOTAL	16
PRESSURE REGULATOR	TOTAL	12
TEMPERATURE TRANSDUCER	TOTAL	24
PRESSURE TRANSDUCER	TOTAL	24
FLOW CONTROL ORIFICE	TOTAL	4

Figure 4.1-2 Selected System Schematic

housed in the forward skirt and nose cone section of the vehicle. This provides for compact installation and easy servicing. An installation sketch of the selected system is presented in Figure 4.1-3. It should be noted that fill and drain lines/valves are not shown in this sketch. Plumbing details for the system including line lengths, bend radii, line sizes, etc. are presented in Appendix F of this report.

The requirements for the control system (Table 4.1-1) were derived from the pressurization system requirements discussed in section 1.2 of this volume. Several control system schemes were evaluated during the optimization efforts. The selected control configuration is summarized in the following paragraphs.

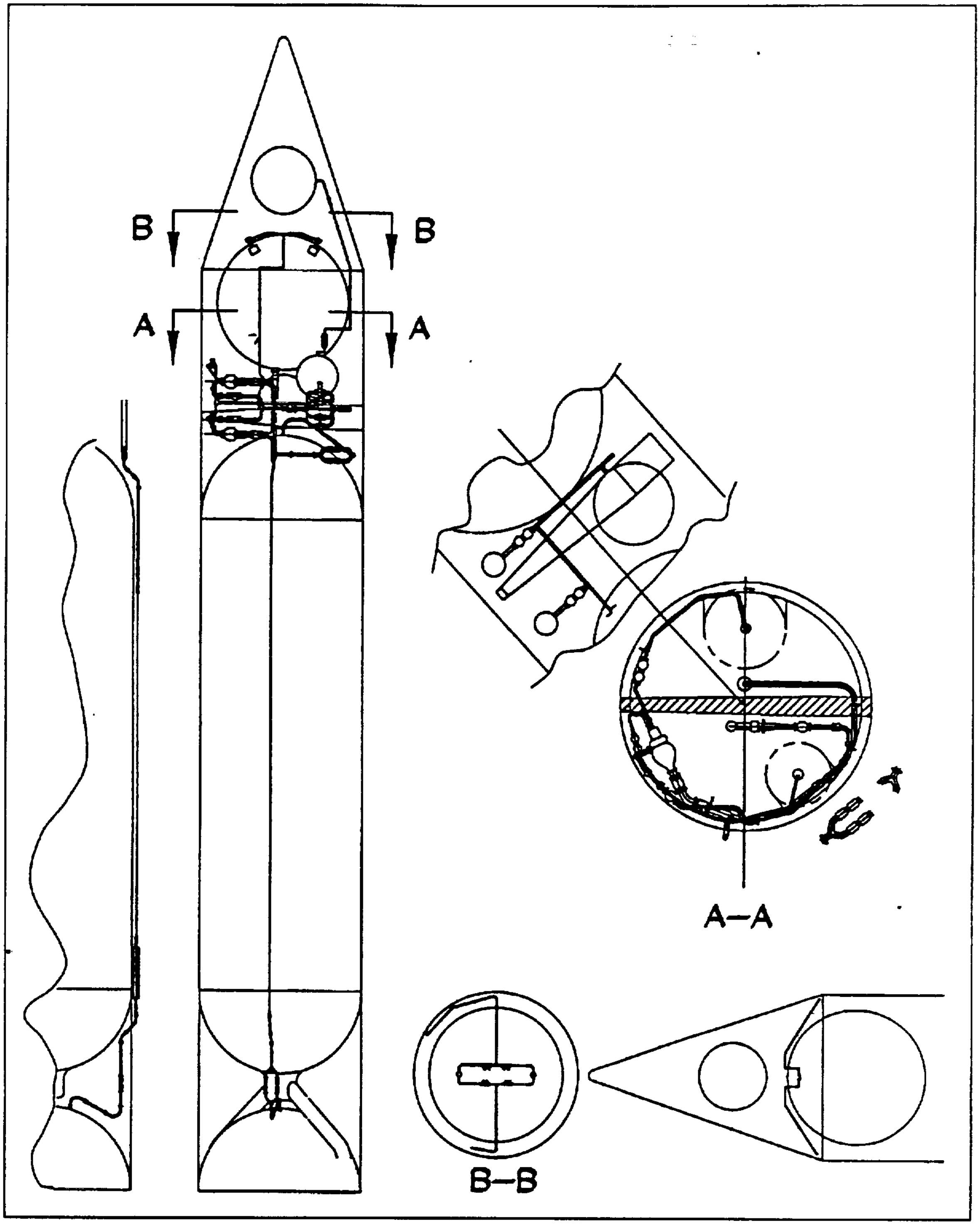


Figure 4.1-3 Flight Vehicle LO2/LH2/He Heater System Installation

Fuel and LO2 Tank Pressure Control - Both the LO2 and RP-1 tanks operate at the same pressure. This pressure is constant throughout booster flight. Booster engine thrust changes are accommodated by throttling the pressurant flow to the tanks. The helium pressurant flow is controlled by a network of parallel orificed valves upstream of the helium heater. The on/

Table 4.1-1 Control System Requirements

• Oxidizer and fuel tank pressures to be controlled to within ±5.0 percent
• The primary heat source is used to heat the helium to constant temperature
• The secondary heat source will be sufficient to maintain enough pressure in the helium tank to complete the 120 second mission
• Initial ullage volume of 5%
• Maximum LO2 and RP-1 ullage temperature is 800 °R
• Maximum helium pressurant temperature exiting primary heat source is 1000 °R
• Maximum system LO2 volume flow rate is 112.4 ft3/sec
• Maximum system RP-1 volume flow rate is 65.9 ft3/sec
• The system shall accommodate engine throttling of 75% at t+30 sec to prevent exceeding vehicle max Q limits
• The pressurization system shall have no operational crit 1 failure modes. The control system shall handle full component redundancy

off valve network is designed to accommodate engine flow changes and the failure of one valve. The valves are controlled by propellant tank pressure. These valves are shown between plumbing locations I and E on the pressurization system schematic (Figure 4.1-4).

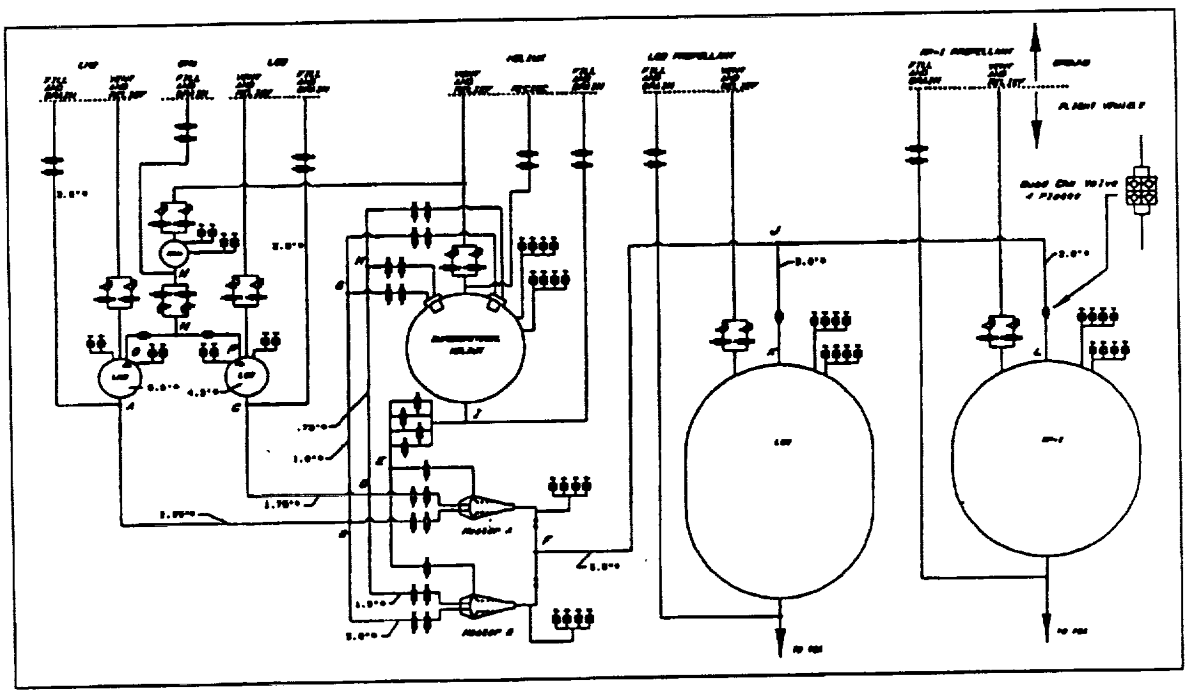


Figure 4.1-4 Flight Vehicle Pressurization System Flow for Selected System

Pressurant Temperature Control - The primary heat source is an oxygen/hydrogen heater with a helium diluent and provides a pressurant temperature at the heater outlet of 900-1000°R. Hydrogen and oxygen flows are controlled in unison to maintain the heater outlet temperature. The oxygen/hydrogen flow ratio is maintained to provide a stoichiometric mixture into the heater. The pressure of the LH2 and LO2 tanks is held at a constant level above the supercritical helium tank pressure. This allows the control valves and heater injectors to operate with a constant pressure drop across them. These control valves and the heater outlet temperature transducers are shown between plumbing locations B/D and F in Figure 4.1-4.

Helium Tank Heat Addition - The secondary heat source is an oxygen/hydrogen heater located in the helium tank. The hydrogen and oxygen flow rates to the secondary heater are maintained at a stiochiometric mixture ratio by orifice selection and the constant pressure drop across the orifice and injector in combination. This provides a constant heat addition to the helium tank. These control elements are shown between plumbing locations G/H and the helium dewar in Figure 4.1-4.

The control system provides for normal operation at both 100% and 75% engine thrust levels and reliable operation through full system redundancy. System redundancy provides for the shutdown and isolation of a failed component. Single branch components in all parallel branch systems can accommodate the full range of operating scenarios. Flows can vary from 37.5% to 100% of design system flow. The system is designed to fail operational. A failed component such as a heater high/low temperature condition will be sensed, and the component will be isolated and shutdown. Concurrently, the parallel component will provide twice the flow to accommodate system needs. These are also check valve sets in the system which prevent the inadvertent backflow of LO2 into an LH2 or RP-1 system and vice versa.

A vehicle engine-out condition is handled by the vehicle engine controls and is essentially invisible to the pressurization system.

Appendix G of this report presents the results of controls concept definition and modeling analyses done by Honeywell in support of the PTPSTP.

4.2 MAJOR COMPONENTS DESCRIPTION

The major components of the selected flight pressurization system are the helium pressurant storage dewar, the O2/H2 helium heaters (primary and secondary) and the system valves.

Pressurant Storage Dewar - The helium pressurant storage dewar is a spherical heavy wall tank capable of holding 14,000 lb of supercritical helium (P=3000 psia and 40°R). The preliminary design concept is a welded tank of aluminum-lithium material insulated with spray-on foam insulation. The tank is approximately 13 ft in dia. The helium will be preconditioned by a ground conditioning system as it is loaded into the tank. The pressurant will be maintained at proper storage conditions prior to launch by a ground recirculation/ cooler system.

Primary Heater - The primary O2/H2 helium heater is a cylindrical unit with an LO2/LH2 fed injector and burns LO2 and LH2 at near stoichiometric (O/F = 8) conditions. The combustion flow is mixed with cold helium diluent to produce tank ullage pressurant at a temperature between 900-1000°R. A current design concept, shown in Figure 4.2-1 utilizes a turbulence ring to promote mixing between the hot O2/H2 core flow and the cold helium diluent. Valves control the LO2, LH2 and helium diluent flows. The heater has the capability of being throttled to 37 1/2% of full flow to satisfy all of the system operations requirements, i.e. max Q throttle, engine out, heater out. Details of the heater design concept are presented in the Aerojet final report (Appendix B).

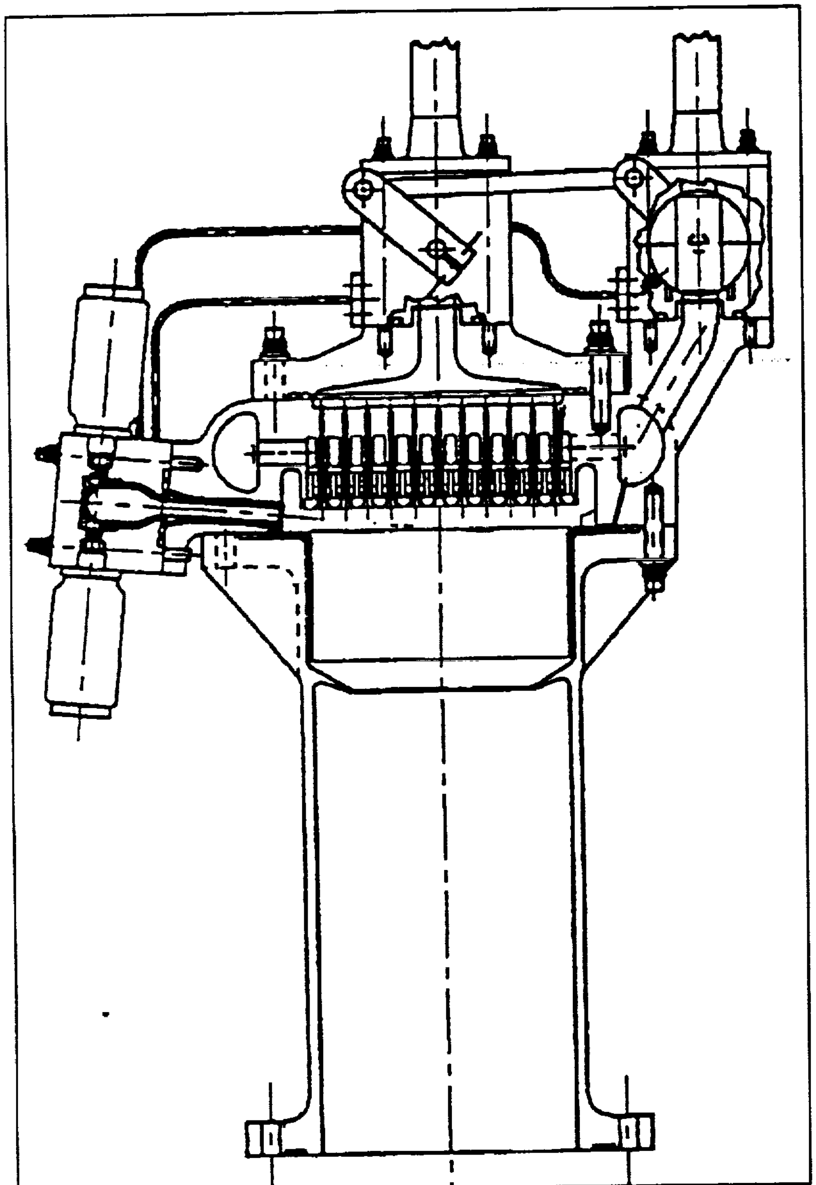


Figure 4.2-1 Primary Helium Heater Concept

Secondary Heater - The secondary O2/H2 helium heater must be a compact unit that can transfer the O2/H2 heat of combustion to the helium pressurant in an efficient manner to ensure proper expulsion of the helium from the storage dewar. This unit must be designed for reliable ignition and operation in a cryogenic helium environment. The current design concept uses a dewar tank wall-mounted unit exhausting directly into the stored helium. The selected system provides two secondary heaters for redundancy. The secondary heater design concept is shown in Figure 4.2-2. This unit also operates at near stoichiometric conditions similar to the primary heater. It does not use a cold helium diluent, as does the primary heater, and must be regeneratively cooled by LH2. A torch ignitor ensures reliable ignition in the cryogenic helium environment.

System Flow/Control Components - The following is a brief description of the pressurization system valves, regulators, and orifices required for the flight pressurization system.

Ambient helium stored at 5000 psia is utilized to pressurize the heater propellant tanks. A normally closed, solenoid operated valve (globe, gate, or ball), coupled with a downstream

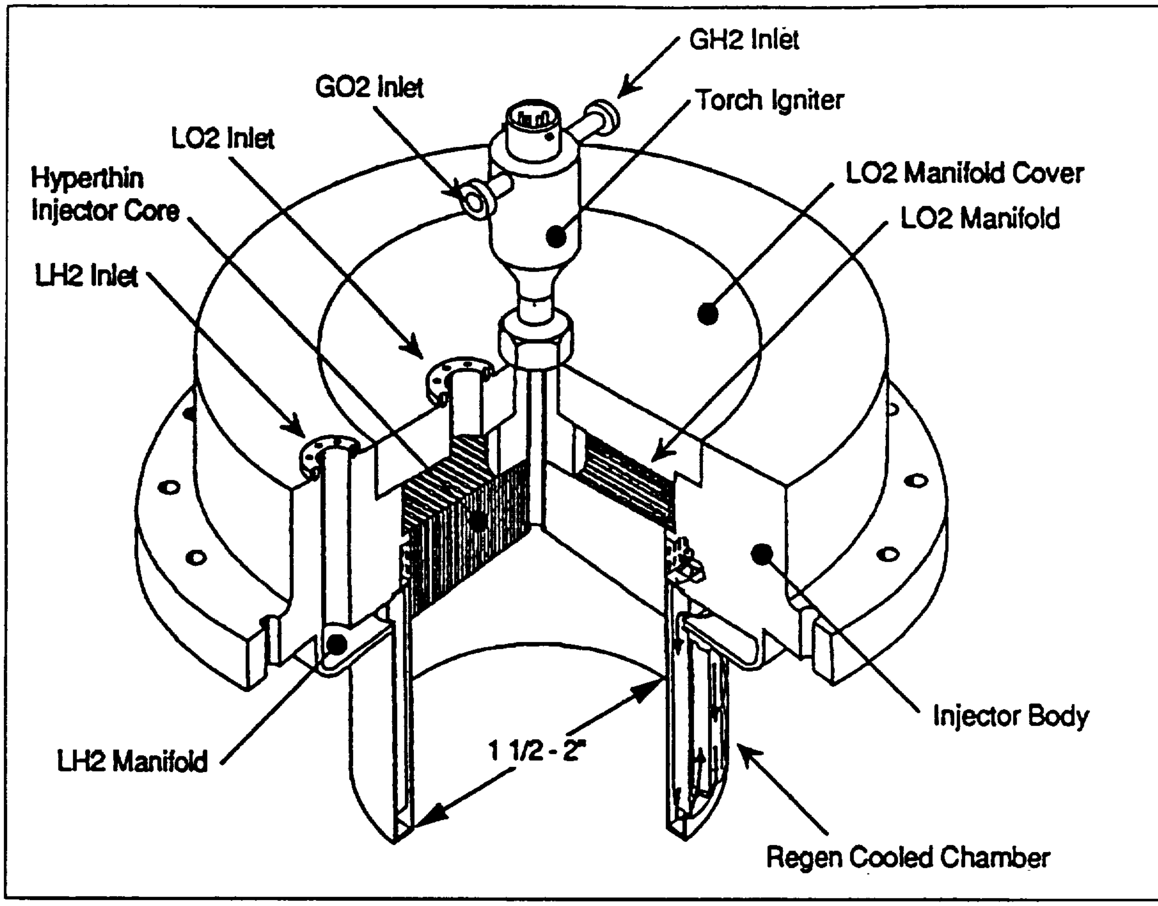


Figure 4.2-2 Secondary Heater Assembly

pressure reducing regulator, provides flow control of the helium gas. System redundancy and fail operational capability is achieved through the utilization of a parallel flow path through identical components. Operational pressure and temperature ranges are 4000-5000 psia and 500-530°R. Components are sized for use with 1.0 in. dia lines. Gaseous helium flow is split and routed to the individual propellant tanks (LO2 and LH2). Quad redundant check valve assemblies prevent back-flow and/or propellant mixing should an over-pressure condition occur in the propellant tanks. Operational pressure for the check valve assemblies is 4000-5000 psia. Temperature requirements and service media for the check valves are: liquid oxygen compatibility and 160°R temperature requirement for oxygen pressurization check valves; and, hydrogen service compatibility and 37°R temperature requirements for the hydrogen pressurization check valves.

Control of propellant flow to the primary and secondary heaters is accomplished using dual valves in series. One valve, primarily a shut-off valve, is paired with a control valve to provide mixture ratio control. The shut-off valves have a normally closed, solenoid actuated pilot valve design and provide full flow to the control valves. The control valves have a normally open, solenoid operated pilot valve design with orificed flow for mixture ratio control. Liquid hydrogen valve requirements are 4000 psia operating pressure, 37°R operating temperature, and sizes ranging from 1.0 in. (secondary heater supply) to 2.0 in.

(primary heater supply) dia. Liquid oxygen valve requirements are 4000 psia operating pressure, 160°R operating temperature, and sizes ranging from 0.75 in. (secondary heater supply) to 1.50 in. (primary heater supply) dia.

Primary heater helium flow is regulated with a four path parallel valve network which supplies both primary heaters. A normally closed, solenoid operated shut-off valve is utilized to provide heater isolation in the event of heater failure. The regulating network consists of four normally closed, solenoid operated pilot valves with orificed flow arranged in parallel to provide incremental flow-rate control. Design criteria for these valves are 3000 psia operating pressure, 40°R operating temperature and 0.5 sec maximum response time.

The heated exhaust gases (helium/steam mixture) from each primary heater are collected in a manifold and distributed to the vehicle main propellant tanks (LO2 and RP-1). Dual, series arranged check valves are located at the outlet of each heater to prevent back-flow and provide isolation of the heater in the event of heater failure. These check valves will be designed for low-pressure drop, 1500-2000 psia operating pressure and 1000°R operating temperature. Quad redundant check valve assemblies, located in the individual tank distribution lines, prevent back-flow and/or propellant mixing should a main propellant tank over-pressure condition occur. The requirements for these check valve assemblies are the same as the heater outlet check valves described above. The line diameters for the check valves are as follows: 5.0 in. dia for each individual heater; 3.0 in. dia for LO2 tank pressurization; and, 2.0 in. dia for RP-1 tank pressurization.

Vent and relief valves are required for all propellant (LO2, LH2, LHe, GHe, and RP-1) tanks. Prelaunch vented propellants will be ducted overboard through umbilical disconnects to the appropriate vent or burn stack. High operating pressure, low response time, material compatibility and minimized leakage must be considered in the design of these valves and related hardware in order to provide high system reliability.

5.0 TECHNOLOGY ACQUISITION PLAN

5.1 TECHNOLOGY NEEDS

The following technology needs for a pressure-fed LRB or HRB pressurization system were identified during the flight system trades and system optimization studies.

Water/Ice Management - The selected flight system will introduce small amounts of water into the system from the primary flow helium heater and the secondary Helium heater. The water will form ice in the Helium storage dewar and ice in the main LO2 tank. It will be deposited in the form of condensation in the RP-1 tank. Understanding and controlling the effects of this water/ice is considered an enabling technology.

High Efficiency Helium Heater (Primary) - The helium heater used as a primary pressurant heat source in the selected flight system must be a high efficiency unit that can maximize the transfer of the O2/H2 heat of combustion to the helium pressurant. Achieving this in a durable, stably operating, compact unit is considered an enabling technology. In order to demonstrate technical feasibility of the proposed system, depicted in Figure 5.1-1, several key technologies will be explored using one quarter scale heater component tests performed at Aerojet and system tests performed at MSFC. The technologies of primary concern are related to the startup and operation of the system over the entire throttle range of the heater.

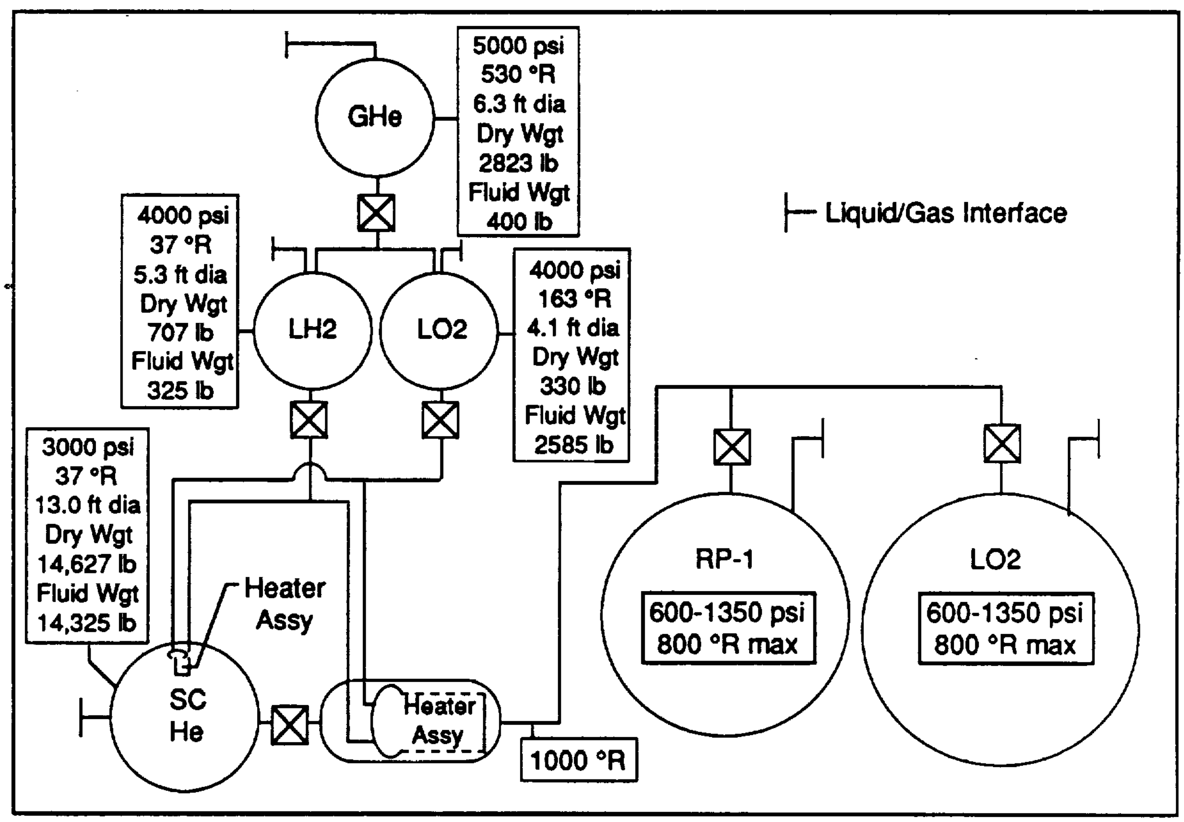


Figure 5.1-1 Selected Pressurization System Schematic

Table 5.1-1 Technology Needs for Subscale Testing of Primary Heater

Mixing efficiency of reactants and pressurant
Variation in mixed gas products properties over expected operating range
System stability over expected operating range
Ignition and start-up characteristics (using helium lead)

Table 5.1-1 presents technology "needs" to be addressed in subscale testing of the primary heater.

High Efficiency Helium Heater (Secondary) - The helium heater used as a secondary pressurant heat source in the selected flight system must also be a high efficiency unit that can transfer the O2/H2 heat of combustion to the helium pressurant in the storage dewar to ensure efficient dewar expulsion. Achieving this with a durable compact unit that can operate in a cryogenic helium environment is considered an enhancing technology.

As currently planned, the technology acquisition plan does not include design, fabrication, or testing of the secondary heater in the quarter scale test article. One of the major concerns is reliable ignition of the secondary heater in the helium dewar environment. The proposed testing of the primary heater will provide some insight to potential ignition problems of the secondary heater. The similar, but not as severe, environmental conditions for the primary heater will define which environmental control techniques, i.e., initial isolation or preheating, will be required to ensure reliable ignition. Table 5.1-2 summarizes which technologies are directly applicable to both the primary and secondary heater.

Table 5.1-2 Technology Acquisition Applications

Technology Issues	Primary Heater	Secondary Heater
Mixing efficiency of helium primary heater	X	N/A
System stability over operating range	X	N/A
Ignition and start-up characteristics	X	X
Mixed gas properties over expected operating range	X	N/A

Helium Dewar Expulsion Process - An efficient helium dewar expulsion process is desirable for the selected flight system. Test data have indicated that temperature stratification in the helium dewar can improve the expulsion process with a smaller secondary heat source. Understanding and controlling the secondary heat input and heat transfer to the helium pressurant in the helium dewar is considered an enhancing technology.

5.2 TECHNOLOGY PRIORITIZATION

The pressurization system technology needs were prioritized, and the relative risk to the flight system and a large subscale test system have been evaluated. This prioritization and risk assessment was necessary to properly allocate budget resources and assign the technology acquisition tasks to PTPSTP Tasks III and IV. The prioritization and risk assessments of the four identified technologies are presented in the following paragraphs.

Water/Ice Management - Water/ice management is a first priority, low risk, enabling technology. As such it was assigned to Task III analysis and will be part of the technology test bed (TTB) contamination test at NBS.

The pressurization system will introduce small amounts of water into the vehicle system. Although this ice is not expected to be detrimental to system performance, an assessment of its effects must be performed. The primary heater will introduce water into the main pressurant flow. This will be in the form of water vapor until it reaches the main propellant tanks. Small amounts of ice are expected to form in the LO2 tank and a small amount of water will be deposited in the RP-1 tank. A secondary heater would introduce water into the helium storage vessel, forming ice. The properties of the ice and how much may be retained in the helium vessel will be determined. The analysis efforts in Task III will answer these questions sufficiently for test system design. Questions relative to ice formation in the helium dewar will be answered by water or steam injection tests in the TTB testing at NBS.

High Efficiency Heater-Primary - A high efficiency primary heater is a first priority, moderate risk, enabling technology. As such it was assigned to Task III for analysis and testing.

Development of a high efficiency helium heater is essential to proof-of-concept on the selected flight system. Because of similar technology work ongoing in the propulsion industry, demonstration of the primary heater is not considered difficult. It is anticipated that analysis efforts in Task III will answer technical questions sufficiently for test article design. Large subscale testing in Task III will provide proof-of-concept.

An injector will be designed for the combustor which will ensure that combustion is complete within inches of the injector face; thereby giving a uniform temperature of the reactants. For this reason, the majority of the technology issues are related to the presence and mixing of the helium with the reactants.

High Efficiency Heater-Secondary - A high efficiency secondary heater is a second priority. low risk. enabling technology. We decided to use Task III primary heater tests for a partial evaluation and to defer analysis and tests of the secondary heater to Task IV.

Development of a high efficiency secondary helium heater is necessary for the selected flight system concept, but it is considered a product of normal evolution from primary heater development activities. Alternate means of helium dewar pressurization will be employed for the large subscale test article (i.e., ambient hydrogen). Combustion and cooling questions for the secondary heater can be answered by similar technology demonstrations on the primary heater. Analysis and test of secondary heater concepts are deferred to Task IV technology testing or later efforts.

Helium Dewar-Expulsion Process - The helium dewar expulsion process is a second priority, low risk, enhancing technology. As such it was assigned to Task III analysis.

System performance has been bounded by analysis from 100% mixing to full stratification. The system will operate between these two extremes. There is no significant system payoff for performing subscale tests on this technology element. Heat that can be eliminated from the secondary (dewar heater) must be added at the primary heater. In addition, the results of complex and expensive small subscale tests are difficult to scale to large storage dewars. There are two advantages and one disadvantage of a fully stratified dewar expulsion system:

Advantage	~40% less steam in dewar
Advantage	~200°F lower temperature excursion of helium supplied to primary heater
Disadvantage	Additional critical hardware, i.e. diffuser.

5.3 TECHNOLOGY ACQUISITION/DEMONSTRATION

After the technology needs have been identified and prioritized, it is necessary to determine the most cost effective way to acquire and demonstrate the required technology. This can be done by analysis, small subscale tests, large subscale tests, or a combination of these. An evaluation was done for each technology, and a determination was made on the most cost effective way to acquire and demonstrate that technology.

Summaries of these evaluations for each technology are as follows:

Water/Ice Management - Water/ice technology issues are ice location, form, distribution and adhesion in cryogenic tanks, water phase and behavior, and ice plugging in the primary helium heater.

Analysis and the TTB tests being done at NBS were chosen as the means to acquire and demonstrate the water/ice management technology for the PTPSTP. Analysis is expected to approximate the water/ice phenomena with sufficient accuracy to support preliminary system and component design. An effective approach for partial technology acquisition is system analysis and modeling. The TTB testing at NBS will provide data on ice formation and properties in a cryogenic dewar. The test and analysis costs are low and the results are considered scalable to full size hardware.

Issues such as effects of small amounts of ice in the helium heater, and ice and/or water behavior in the helium dewar and main propellant tanks are not considered critical technology issues. Detailed demonstration is planned for PTPSTP Task IV testing.

High Efficiency Heater (Primary) - Efficient mixing of the O2/H2 reactants with the helium diluent is essential to system reliability and performance. Variations in mixed gas properties and system pressure drop data are needed for control system modeling. System stability is another technology issue. Low frequency stability under deep throttling conditions is essential. Characterization of ignition and startup characteristics is an important technology issue also. Component testing at Aerojet is a cost effective way to examine these technical issues with the exception of system interactions and pressure drop. Large subscale system testing on the 116 test position at MSFC will expand and verify the Aerojet test database and provide realistic system performance information for a reasonable cost.

The large subscale testing on the 116 test position will provide data on loss coefficients of various system plumbing sections with realistic flows. Results should be scalable to a flight system design. The 116 testing will also yield data on the system interactions. The understanding of interactions between components such as the primary helium heater, the pressurant dewar and the secondary heat source will be acquired. The low cost of the 116 testing provides an excellent technology return for the investment.

High Efficiency Heater (Secondary) - Satisfactory ignition of the secondary heater in a cryogenic helium environment is the primary technology issue for the secondary heater. The technology acquisition method proposed for the secondary helium heater consists of use of large primary heater test data for analysis and preliminary design of the flight secondary heater. Use of large subscale primary heater test data is expected to bound the secondary heater ignition problem.

Analysis and preliminary design of a flight secondary heater is desirable, but is deferred to PTPSTP Task IV in the technology acquisition plan. Analyses will include injector hydraulic analysis, injector combustion performance, and a literature review and modeling of the ignitor flow. This modeling effort will determine the ignition energy required and define the severity of the ignition problem.

The secondary heater technology acquisition efforts are considered enhancing because an ambient helium cascade system is a backup method for secondary heat addition if a secondary helium heater is not feasible.

Helium Dewar Expulsion Process - Helium dewar expulsion issues include temperature stratification, fluid mixing and circulation, heat transfer, secondary flow impingement, phase change diffusion and heat addition, momentum transfer, and primary outflow. Analysis of these issues is low cost and results are expected to be sufficient for system design. Small subscale test costs are high and results are difficult to scale to larger sizes. Large subscale test results are good, but costs are fairly high. Analysis is the chosen methodology to acquire this technology. The analysis is expected to give a good first order approximation of the phenomena associated with dewar expulsion.

As was discussed in the technology prioritization section, the pressurization system will work with whatever level of stratification and mixing that exists in the helium dewar, from fully stratified to fully mixed. Any secondary heat addition saved by stratification must be replaced by additional energy added in the primary heater. This categorizes helium dewar expulsion as a second priority, enhancing technology. This technology acquisition would give an indication of minor impacts to system efficiency and does not, therefore, warrant more than the analysis effort planned.

5.4 TECHNOLOGY ACQUISITION PLAN SUMMARY

The detailed technology acquisition plan for the PTPSTP is presented in Appendix B of this report. The plan, developed in Task II of the PTPSTP, presents how the technologies identified in Task I, Flight System Optimization and Selection, can be acquired and demonstrated in Task III or IV of the program. The plan discusses the four technology needs identified, including the priority rationale, the methods of acquisition/demonstration, the rationale for method selection, and the detailed acquisition plan for that technology. Each detailed technology acquisition plan includes a task description, work breakdown structure (WBS) task flow, schedule, and cost estimate. In addition to the individual technology acquisition plans, a task was included in the plan called post-test technology assessment. This included subtasks for refinement of the optimized flight pressurization system and integration of the technology "lessons learned" into the PTF pressurization system. PTF integration is a deferred subtask, subject to PTF project approval. The following paragraphs summarize the individual technology acquisition plans for the four identified technologies.

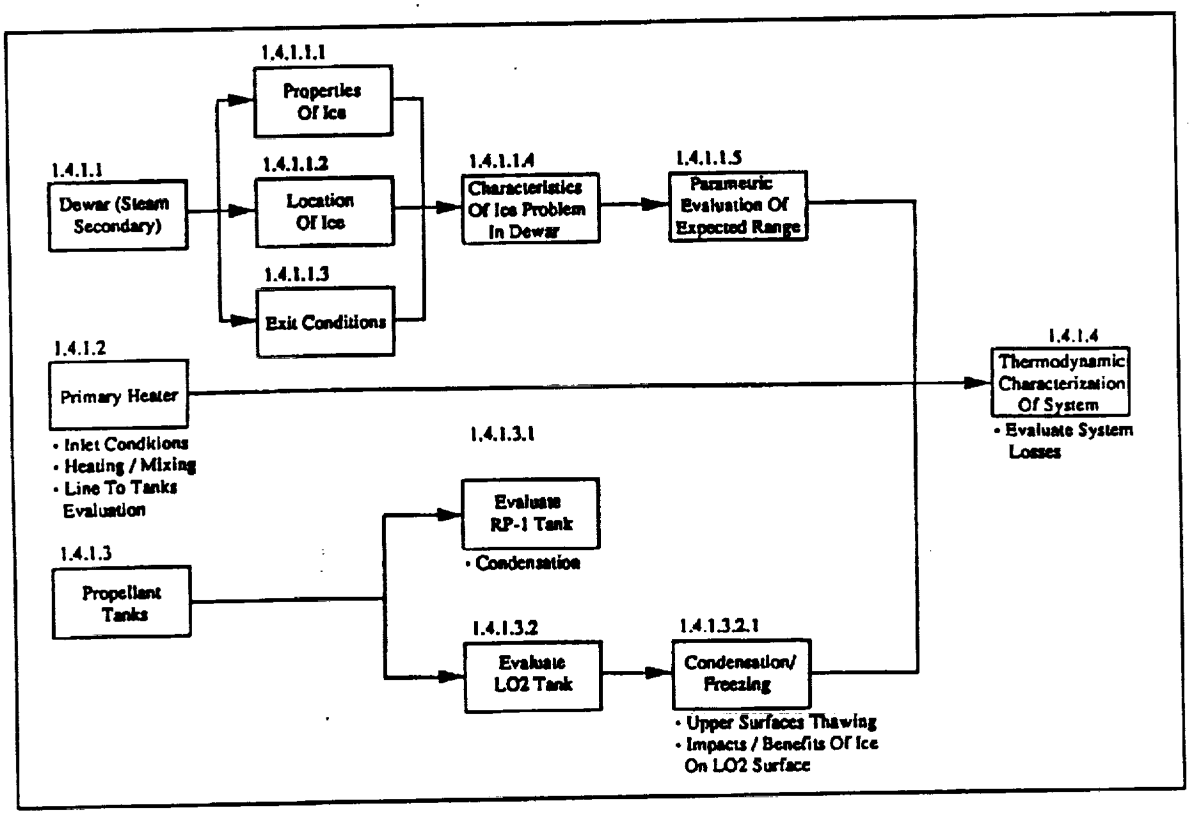


Figure 5.4-1 PTPSTP Task III Analysis (1.4.1)

Water/Ice Management - The water/ice management technology effort has been divided into two parts. Analyses will be performed in PTPSTP Task III to investigate the technical issues associated with water/ice management. NBS TTB subscale testing will be performed to investigate these same technical issues. This testing will develop data to refine the PTPSTP analyses.

The analytical modeling effort will focus on determining the properties and residence time of water/ice formed within the pressurization system. Three distinct areas will be analyzed. These are the helium dewar, the primary heater, and the main propellant tanks.

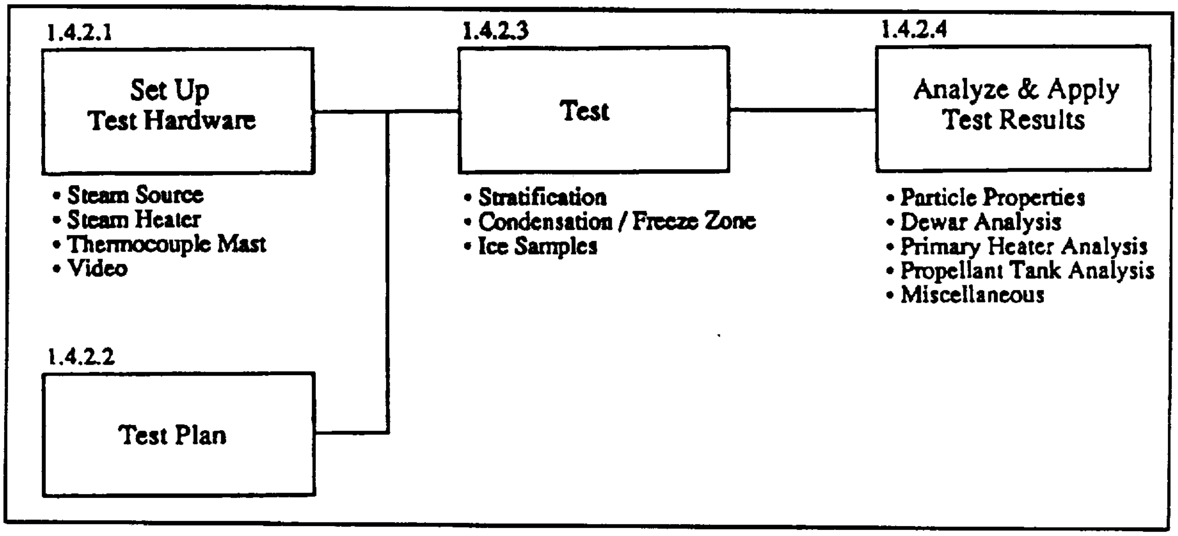


Figure 5.4-2 TTB NBS Test (1.4.2)

The NBS testing effort will collect data related to phenomena in the helium dewar such as density of particles, statistical distribution of variously sized particles, adhesive properties, cohesive properties, and suspension of particles. Activities will include test planning, test hardware setup, testing/data acquisition, and data analysis.

The water/ice technology acquisition WBS and task flow is show in Figures 5.4-1 and 5.4-2.

Primary Helium Heater - Acquisition and demonstration of the technology required for the direct helium heating pressurization system will be achieved through the design, fabrication, development, test, and delivery of pressurization system components sized for a quarter scale flight system.

Aerojet Propulsion Division will perform the technology acquisition required for the primary heater. This heater will be designed for operating conditions appropriate for a pressure-fed propulsion system as defined by Martin Marietta Manned Space Systems. Aerojet Propulsion Division will design, fabricate and test primary heater components, subassemblies, and/or assemblies to the extent necessary to acquire the needed technology.

Technology demonstration will be accomplished through testing of a primary heater assembly designed and delivered for operation on test stand 116 at MSFC.

This technology demonstration of the primary heater on test stand 116 will be made using hydrogen in place of helium as the primary pressurant. This substitution will bedone because of the expense of hardware required to condition helium to supercritical temperatures and pressures and the recurring high cost of helium for each test run. Any deviation from the basic design for helium to accommodate hydrogen for this demonstration must be evaluated and approved by Martin Marietta Manned Space Systems and MSFC.

The initial effort required to design, fabricate, and test the technology demonstration hardware is the definition of design requirements. In parallel with the design requirements definition, work will begin on defining the test objectives. The test objectives must be worked in parallel in order to define instrumentation requirements and the test matrix, both of which will impact the hardware design. Included in the test activities are the engineering support of the testing, test procedures, post-test data analysis, and final reporting of the test results.

The design task will include a definition of design requirements, and preliminary design of the demonstration hardware, heater analysis, and final design of the demonstration hardware. Analysis efforts include injector hydraulic analysis, combustion analysis, mixing analysis, pressure loss analysis, thermal analysis, and combustor low frequency stability analysis. Final design efforts will include a preliminary design review (PDR) and critical design review (CDR).

Fabrication of the demonstration hardware will include the heater assembly (injector, combustion chamber and mixer) proof plates and flow fixtures for testing of the unit. After assembly and preliminary testing, the primary heater will be ready for performance preliminary testing at Aerojet.

Test objectives will be defined for the Aerojet testing and a test plan developed. The test plan will include a definition of test instrumentation and a test matrix. Table 5.4-1 presents a typical test matrix for the Aerojet performance tests.

After testing at Aerojet, the resulting data will be reviewed, analyzed, and documented prior to MSFC system testing with the primary heater. Any anomalies will be resolved prior to testing at MSFC.

Table 5.4-1 Typical Test Matrix

Test Number	Test Type
1-3	System checkout test
4-10	Variable chamber pressure testing to determine low frequency stability limit
11-20	Variable LO2/LH2 and diluent flow to anchor CFD model
21-25	Transient testing to define system response characteristics

Preparation for the MSFC testing will include definition of test objectives and development of a comprehensive test plan for the MSFC tests. MSFC testing will be directed toward understanding the interactions between the primary heater and the rest of the pressurization system including system response and controllability. A typical test matrix for the MSFC testing is shown in Table 5.4-2. After completion of the MSFC testing, the data will be reviewed and analyzed with test results documented in a final report. This report will present recommendations relating to design parameters for the flight hardware.

System Flow Testing (5 tests) Testing to establish system resistance and valve flow characteristics Establish system fill times and valve response times
Open Loop Throttle Testing (10 tests) Single point testing at flow rates of 100 % 75% 50 % 37 %
Closed Loop Testing – system performance definition System simulation (5 tests)

Table 5.4-2 MSFC Typical Test Matrix

The primary helium heater technology acquisition WBS/task flow is shown in Figures 5.4-3 through 5.4-5.

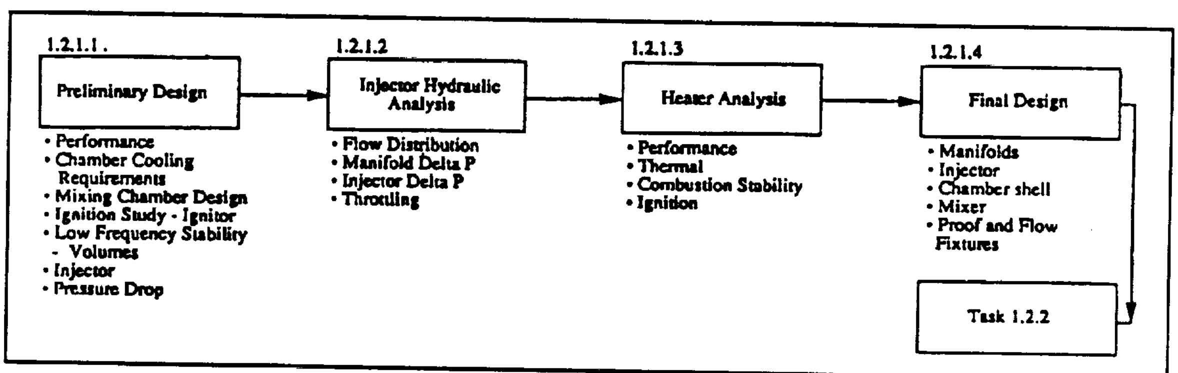


Figure 5.4-3 Technology Demonstration Hardware Design (1.2.1)

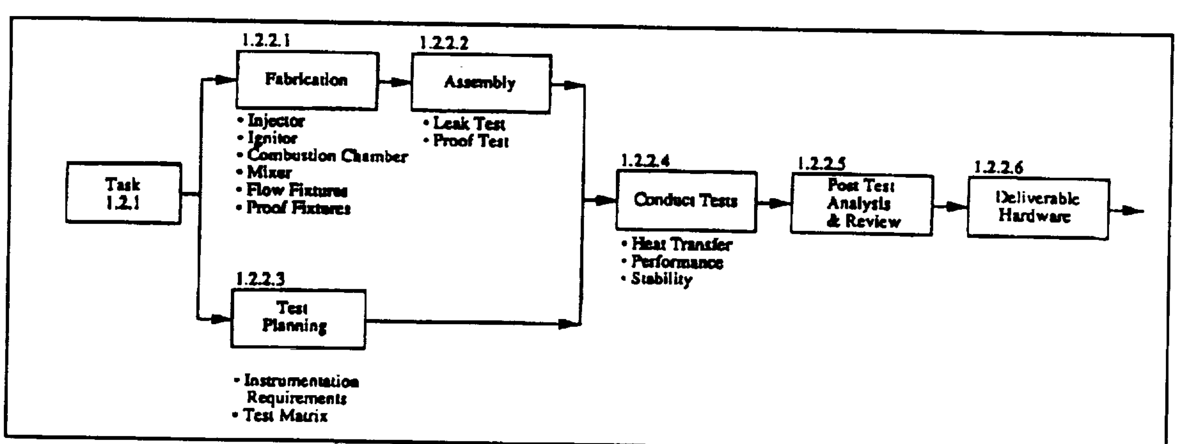


Figure 5.4-4 Hardware Fabrication and Test (1.2.2)

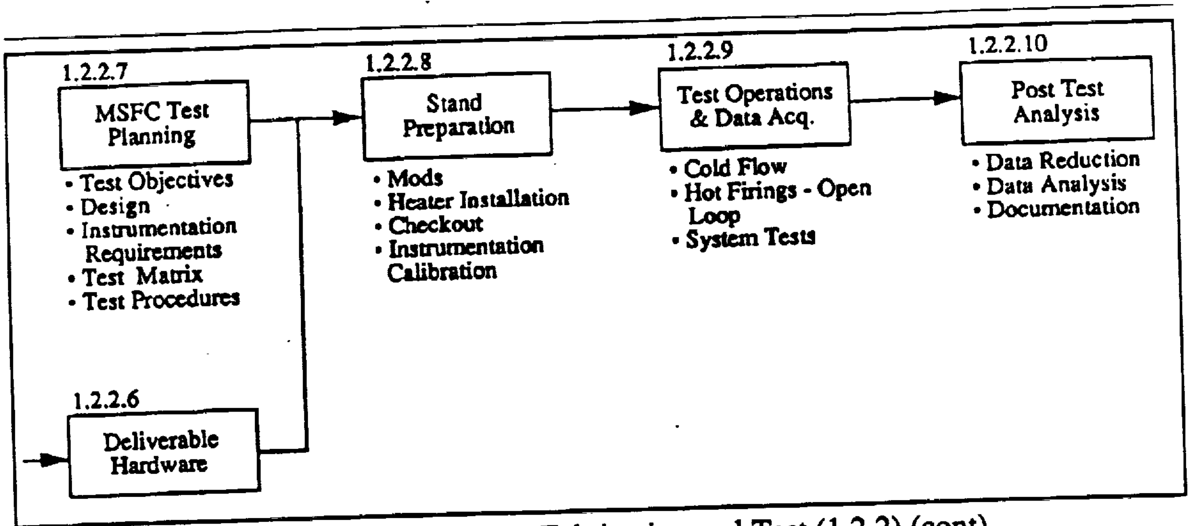


Figure 5.4-5 Hardware Fabrication and Test (1.2.2) (cont)

Secondary Helium Heater - The technology acquisition for the secondary helium heater has been deferred to PTPSTP Task IV.

The technology plan for the secondary heater consists of one major task divided into several subtasks. The task covers the analysis and preliminary design of the flight type secondary heater. A preliminary design of the full scale secondary heater will define the operating parameters and design requirements. The preliminary design will also identify critical design features which may be simulated in one quarter scale hardware in order to validate the design approach. The effort will begin with a definition of requirements and a design for the full scale hardware.

The purpose of this activity is to define the full scale design in sufficient detail to understand technical issues relative to the full scale design. Key full scale features which must be defined include injector configuration, definition of the ignitor design, and operating parameters.

Two major components influence the performance of the secondary heater: the injector and the combustion chamber. The injector and combustion chamber design influences the efficiency of the combustion or energy addition process with the injector having the primary influence. The chamber will influence the thermal performance of the secondary heater as

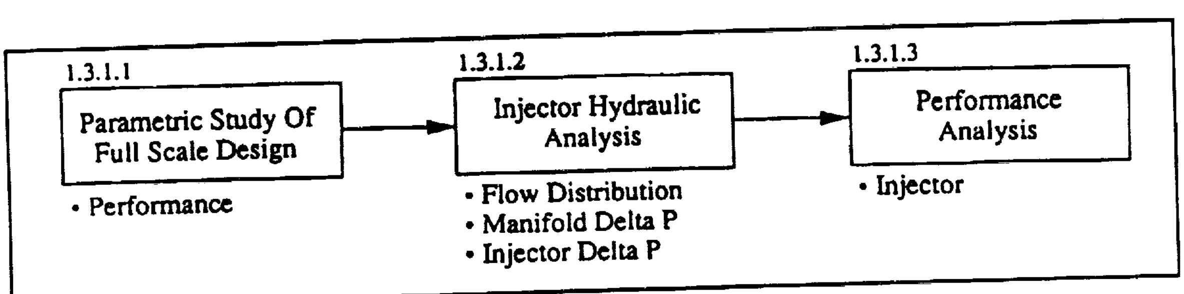


Figure 5.4-6 PTPSTP Task III Analyses (1.3.1)

measured by the absolute temperature of the exhaust products. Included in this task will be the analysis of the combustion performance of the injector. Also included is the modeling of the igniter flow in order to define the thermal environment in which ignition of the main injector flow will occur.

The secondary helium technology acquisition WBS/task flow is shown in Figure 5.4-6.

Helium Dewar Expulsion Process - Analyses will be performed in PTPSTP Task III to examine the technical issues associated with the expulsion of helium pressurant from the helium storage dewar. The helium dewar expulsion technique consists of adding secondary heat to the helium storage dewar with an O2/H2 secondary helium heater. An alternate method to provide secondary heat addition would be the use of an ambient helium cascade system. While ambient helium is a viable, low technology approach, it carries performance, size, and packaging penalties for the launch vehicle, and is, therefore, considered a backup technique for the purpose of the PTPSTP.

The analytical modeling effort will focus on describing the thermodynamics of a large cryogenic helium dewar with a high discharge rate and secondary heat (enthalpy) introduction. The analysis methodology developed will support either technique of secondary heat addition.

There are two primary approaches to achieving the high-pressure long duration flow from a cryogenic dewar necessary for PTPSTP success. The enthalpy introduced into the dewar can be in a stratified layer or mixed into a homogeneous fluid. The analysis outlined below is necessary to characterize the expulsion process and develop the performance and hardware requirements for implementation of either heat addition approach into the technology demonstration hardware.

Our approach to the analysis is to create an analytical model that can be used to evaluate different techniques that promote stratification within the supercritical helium dewar. The model will provide predicted data to establish:

Thermodynamics of a cryogenic dewar with two distinct thermal nodes,
Effect of condensible gases (steam) on a stratified system,
Flow rate requirements of gas to the hot node,
Diffuser requirements for the hot node,
Supercritical helium discharge characterization,
Effects of frozen condensible in system (incorporating NBS ice results into the model), and
Evaluation of mixing zone between hot and cold nodes.

A second analytical model will be developed to evaluate different techniques to promote mixing of a hot gas into a cryogenic dewar to achieve a homogeneous mixture that has sufficient enthalpy to sustain the high discharge flow rate of the system. The model will provide predicted data to establish:

Thermodynamic cycle where one gas condenses and freezes upon mixing (steam),

Thermodynamics of mixing of two gases using non-ideal gas criteria,

Time to complete thermal equilibrium of injectant gas,

Properties of condensed/frozen components (incorporating NBS ice results into the model),

Evaluate condensed/frozen components escaping from dewar (parametrically) and their impact on performance of the system,

Effect of hot steam impingement on dewar vs. time,

Total system losses to dewar wall, and

Difference between helium and hydrogen pressurant for initial test purposes.

The results of these analyses will then be integrated into a total expulsion system model.

The helium dewar expulsion process technology acquisition WBS/task flow is shown in Figure 5.4-7.

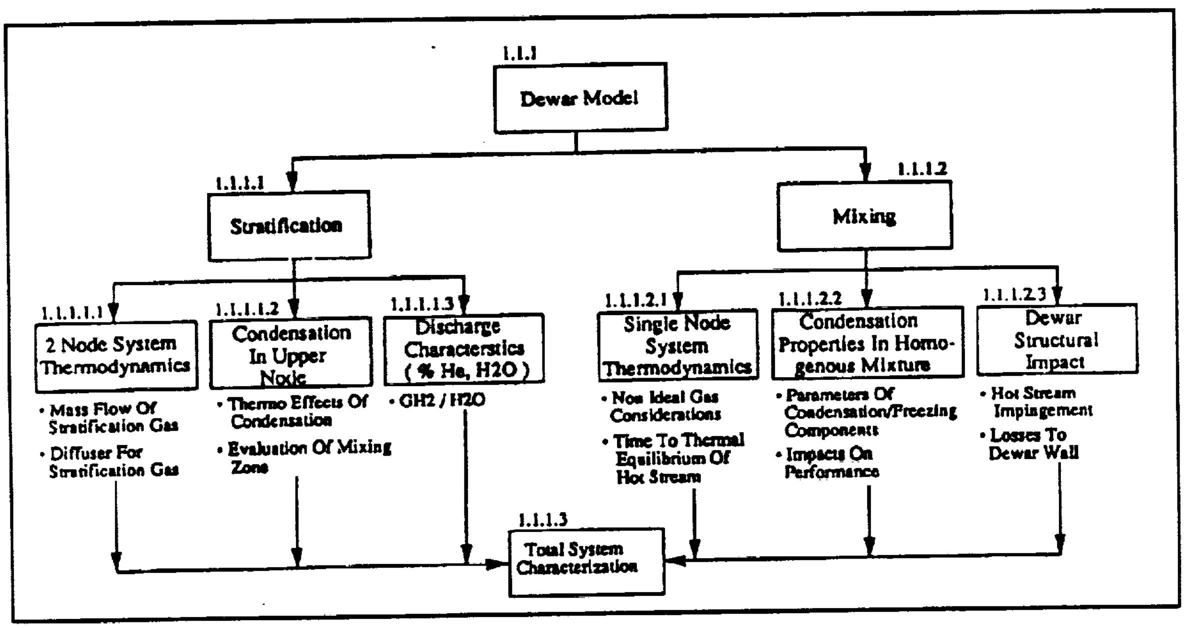


Figure 5.4-7 PTPSTP Task III Analyses (1.1.1)